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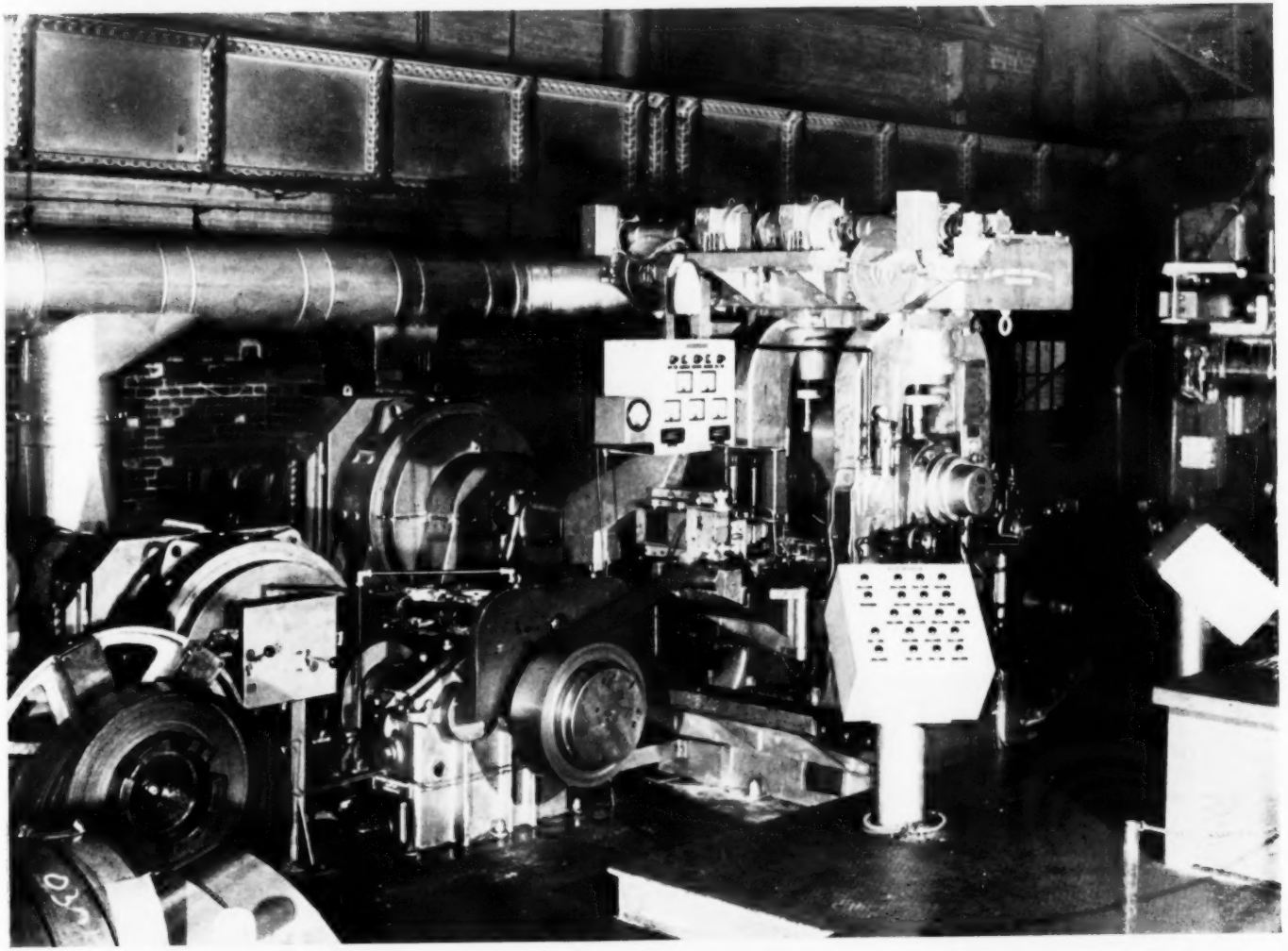


Fig. 26.—Single-stand cold strip mill of Steel Peech & Tozer, built by Sir James Farmer Norton & Co. Ltd., showing strip passing through the mill between the coilers. The forced-ventilated motors driving the mill and left coiler can be seen in the background

Electrical Controls in the Steel Industry

By J. C. CHRISTIE, B.Sc., A.M.I.E.E., Chief Engineer, Mining Division (formerly of Metal Industries Division), and J. TUDOR JONES, A.M.I.E.E., Metal Industries Division.

PART II

Part I of this article was published in the September 1959 *issue of this journal, volume sixteen, number three, page* 32.

SINGLE-STAND COLD STRIP MILLS

While hot strip mills may be used to roll steel down to less than 0·05 inch thick, most steel products below this thickness are cold rolled to obtain the benefits of improved surface, temper and accuracy of gauge. Unless large quantities of a single product are required, the cold rolling usually takes place in a reversing single-stand mill in which the strip is passed back and forth between the rolls, which are brought closer together on successive passes. The rolls are normally driven by a motor having simple Ward-Leonard control with an additional speed range by shunt field control. This shunt field range allows the maximum torque needed on the earlier passes where high speed is less essential, but gives the higher speeds on the final passes for which the coil of strip has become much longer.

The control of the coiler drive however is far more exacting. The strip passes between reels which alternately pay it out and coil it up under tension. The tension serves a dual purpose ; firstly a tight coil is self supporting and is more readily handled away from the mill, and secondly the tension helps to pull the strip straight in rolling when otherwise it would tend to wander across the mill. In this way it enables heavier reductions to be taken and gives a flatter and straighter strip than would otherwise be possible.

The accuracy of tension control needed varies with the type of mill and the product being rolled. In some cases the tension needs to be fairly near

CE Current exciter
CG Coiler generator
CM Coiler motor
CVE Constant-voltage exciter
MA Magnetic amplifier
MG Mill generator
MM Mill motor
PE Pilot exciter
PM Pilot Motor
RE Reference exciter

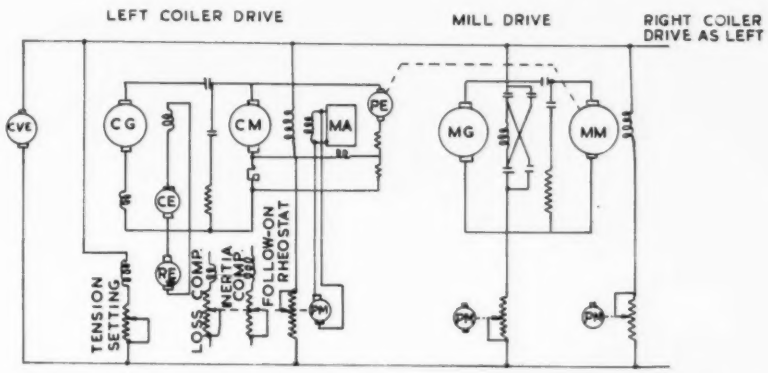


Fig. 27.—Basic control scheme for single-stand cold reversing mill

to the yield point of the material and requires accurate control to provide sufficient stress without the excess which would cause strip breakage. In other cases tension sufficient only to prevent a slack coil is needed.

A typical single-stand cold strip mill is shown in Fig. 26. This is a reversing mill with a top speed of 1500 feet per minute. The mill rolls are driven through gearing by a 240 h.p. d.c. motor with a shunt range of 286 to 955 r.p.m. The coilers either side of the mill are designed for coils of up to 51 inches diameter on an 18 inch mandrel. The coiler motors are rated at 130 h.p. over a speed range of 280-775 r.p.m.

The control scheme is indicated in simple form in Fig. 27. The mill motor MM is supplied by its own Ward-Leonard generator MG, the field of which is controlled by the motorised rheostat in series, which is graded to give uniform acceleration of the mill. Contactors enable the generator field to be reversed to give either direction of rolling. The motor field is pre-set by a separate motorised rheostat to give the required maximum torque or speed for the particular reduction.

The coiler control is designed to give accurately the tension set by the operator under all speeds of rolling and during the acceleration and deceleration at either end of the coil. To obtain the necessary accuracy the control is divided into two functions :—

(*a*) The motor field strength is maintained proportional to coil diameter.
(*b*) The motor armature current is controlled to give the required tension.

The following equations show the merit of this.

Mechanically : $\bar{T} = \dfrac{TD}{2G}$

Electrically : $\bar{T} = k_1 I \Phi$

$\therefore T = I\Phi \dfrac{k_1 2G}{D}$

where

$\bar{T}$ = motor torque (lb-ft)
T = strip tension (lb)
D = coil diameter (ft)
G = coiler drive gear ratio
k_1, k_2 etc. are arbitrary constants
I = coiler armature current
Φ = coiler motor flux.

If $\Phi = k_2 D$

then $T = I\, k_1 k_2 2G$

$= k_3 I$

Thus, if the motor flux Φ is made proportional to coil diameter then the strip tension T will be proportional to the coiler motor armature current I. As it is not possible to measure directly and thereby control the motor flux, the following approach is used.

Mechanically : $N = \dfrac{SG}{\pi D}$

Electrically : $E_M = K_4 \Phi N$

or $N = \dfrac{E_M}{k_4 D}$

where

N = coiler motor speed (r.p.m.)
S = strip speed (f.p.m.).
E_M = coiler back e.m.f.
$k_5 = k_2 k_4 G$

$\therefore \dfrac{SG}{\pi D} = \dfrac{E_M}{k_4 \Phi}$

$\therefore \Phi = \dfrac{E_M \pi D}{S k_4 G}$

If $E_M = k_5 S$

then $\Phi = \dfrac{k_5 \pi}{k_4 G} D = k_2 D$

Therefore if the coiler motor back e.m.f. is maintained proportional to the strip speed, the motor flux is automatically proportional to the coil diameter and, as shown above, the strip tension is proportional to the coiler motor armature current.

These conditions are obtained in the circuit shown in Fig. 27. The strip speed is measured by the pilot exciter PE, coupled to the mill motor. The e.m.f. of this exciter is compared with the back e.m.f. of the coiler motor CM, and any difference is applied to the control winding of a magnetic amplifier MA. The amplifier output supplies a field on the coiler motor so that any difference in

motor and pilot exciter e.m.f. is corrected by a change in the amplifier output.

Providing the e.m.f. difference is small, the motor e.m.f. is proportional to strip speed, and the tension will be proportional to armature current.

As the coil diameter increases during the coiling operation so the motor flux must rise. While the magnetic amplifier can be designed to supply all the field current, more accurate control results from the use of a follow-on rheostat to limit the output required of the amplifier. The main field of the coiler motor is supplied from the constant-voltage exciter through a series rheostat. The rheostat is driven by a pilot motor PM, which is connected across the output of the magnetic amplifier MA. As the amplifier output rises, the pilot motor drives the rheostat, so limiting the control range needed from the amplifier. The follow-on rheostat movement corresponds with coil build-up, and its position gives an indication of coil diameter at any instant.

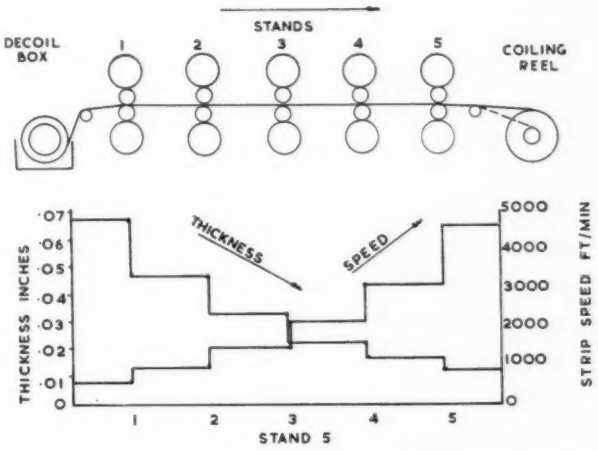


Fig. 28.—Diagrammatic section through 5-stand tandem mill, showing relationship of speed and thickness for a typical reduction

The current control acts through the coiler generator to give an accurate fast response. In order to maintain the armature current proportional to the required tension, two exciters are arranged so that any difference in their voltages is applied to the field of the coiler generator. The reference exciter RE is arranged so that its voltage, controlled by a hand-set field rheostat, is proportional to the required tension. The current exciter CE has its field winding connected in series with the coiler motor armature, so giving an exciter voltage proportional to the motor current. Any difference between the exciter voltages represents an error between the actual and intended motor armature current, but as this difference is applied to the low-resistance field winding of the coiler generator a strong corrective voltage is developed which holds the current error down to a very small value.

The basic equations of the coiler ignored the torque needed to overcome the loss and acceleration torques of the coiler motor. In practice these cannot be ignored as they would tend to give appreciable variation of tension, so that additional fields are provided on the reference exciter to compensate for them.

The loss field takes a signal of speed from the pilot exciter, and the acceleration field from an exciter giving an output proportional to the acceleration rate. Both the effects are variable with coil diameter, and the follow-on rheostat provides a ready means of modulation with changing coil diameter.

TANDEM MILLS

The output of a single-stand mill is limited by the speed of rolling and by the time taken to establish correctly the new setting of the rolls following each reversal. The output can be increased by mounting a number of single-stand mills in tandem, arranged so that the strip is reduced to the required gauge in one pass through the line of stands.

This arrangement, for a five-stand mill, is shown diagrammatically at the top of Fig. 28. Normally a three-stand mill is used for car body sheet gauges, a five-stand mill for tinplate gauges, while a four-stand mill can cover part of either range as well as intermediate gauges.

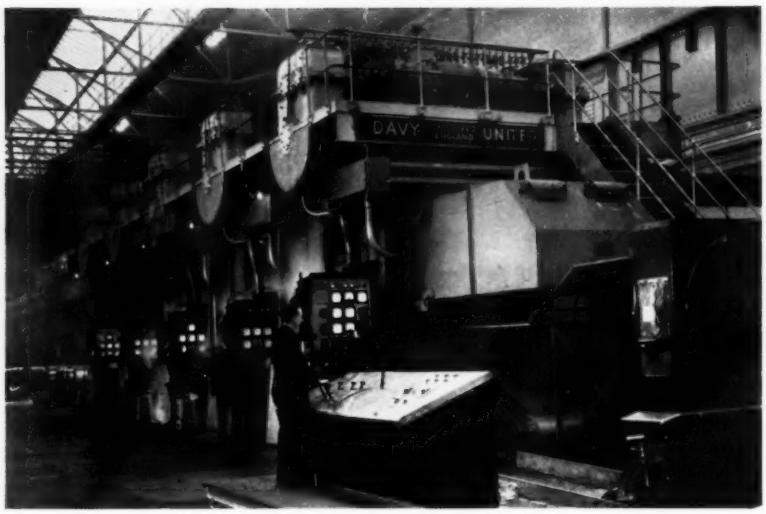


Fig. 29.
Five-stand tandem mill for rolling tinplate at up to 5000 feet per minute in the Ebbw Vale works of Richard Thomas & Baldwins Ltd., seen from the delivery end

The five-stand mill in Fig. 29 rolls tinplate gauges of about 0·010 inch at speeds up to 5000 f.p.m. and is powered by motors having the following outputs.

STAND	H.P.	SPEED (R.P.M.)
1	1750 (single armature)	90–225
2	3500 (double armature)	125–304
3	3500 (double armature)	200–445
4	4000 (double armature)	350–645
5	5500 (triple armature)	500–910
Reel	900 (double armature)	233–1000

From Fig. 28 it may be seen that the strip is in all stands for practically the whole pass time, and good rolling results can be achieved only with an optimum tension in the strip between stands. Too low a tension would allow the strip to wander and, in the extreme, allow slack to develop, while too much tension would break the strip. With the strip under tension the stands are effectively coupled, and as the gauge is reduced in each stand so the length of the strip increases. To maintain the strip under tension the speed of each successive stand must be higher than that of the preceding one by the amount of reduction in gauge in that stand. This is illustrated in Fig. 28.

Special consideration must be given to the control of interstand tension. It is impossible to separate the current taken by each motor to produce the necessary tension, from that needed to provide the rolling torque, and so a current control system similar to that for a single-stand mill coiler cannot be used, although that system is, of course, equally suitable for the coiler on a tandem mill. Interstand tension is therefore produced on a tandem mill by providing the motors with a suitable regulation and adjusting their relative speeds by shunt field control.

The speeds are first set on no load to correspond with the reduction to be taken in each stand, and are then adjusted so that the first stands attempt to go more slowly and the later stands faster than the actual strip. As the stand coupling through the strip prevents this attempted change of speed, a change of load takes place in each motor to produce a tension which is dependent both on the regulation of the motor and the attempted change of relative speed.

Once set up, the tension may be adjusted by the alteration of the shunt field of the motor ; for example if the field of Stand 3 motor is weakened the motor would attempt to go faster, resulting in a reduction of tension between Stands 3 and 4 with an increase of tension between Stands 2 and 3.

The earlier tandem mills used either a common Ward-Leonard generator or a group of generators arranged for parallel operation. The generator voltage range was used for accelerating the mill

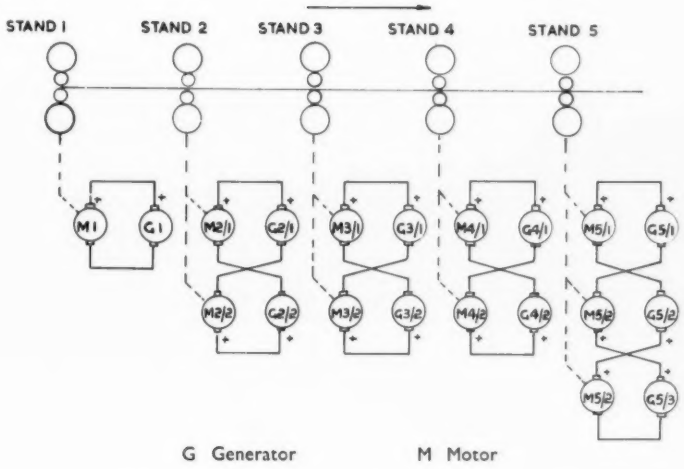


Fig. 30.—Drive arrangement for typical 5-stand tandem mill, showing individual single- double- and triple-armature motor circuits

to the required rolling speed and for setting the speed of the mill as a whole. The shunt fields of the motors were controlled individually to give the relative speeds for the reductions chosen for each stand and to control the interstand tension. This scheme of control is very similar to that used on hot continuous strip and rod mills as previously discussed.

Unlike the hot continuous mills however, a cold tandem mill can only be threaded satisfactorily at a relatively slow speed of say 200-300 f.p.m. As the possible top rolling speeds rose, so therefore did the ratio of speed to be covered by the voltage range of the motors. As the regulation of the motors used is largely due to their armature IR drop, the effect of this became more and more pronounced at the threading speed. Motors designed to have close regulation were used, and did ease this problem, but only by increasing the acceleration problem, as close-regulation motors are larger and consequently have greater inertia.

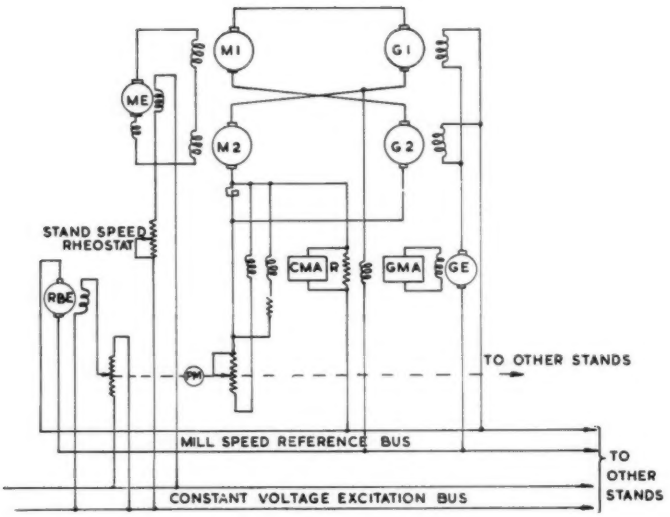
The effect of an excessive regulation at threading speed is to reduce the interstand tension (which is dependent upon regulation) to an unacceptably low level and even to allow the motors to stall in the event of an overload due to incorrect roll setting.

A further disadvantage of the common generator scheme is that as rolling speeds increase so does the power capacity of the generator groups. As there is a practical limit to the size of a d.c. generator, six to eight generators in parallel would be needed for a high-speed tinplate mill.

It is therefore quite natural that the larger high-speed tandem mills have individual generators with some form of closed-loop speed or voltage control. Fig. 30 shows the arrangement of the individual armature circuits for the five-stand mill illustrated in Fig. 29. A tinplate mill characteristically requires greater power on the later stands. The speeds of the motors are fixed by the strip and roll diameter, as no interposed gearing is used. For the slower and lower-power motor for Stand 1 a single-armature motor is feasible, while on Stand 5 the higher power and speed necessitate the use of a three-armature drive. Intermediate stands can use a two-armature design. Where multiple armatures are needed the series-sandwich arrangement as shown in the diagram is used, which both gives inherent load sharing between armatures and avoids cumulative build-up of voltage, so limiting the voltage between any points in the system to the terminal voltage of one motor.

The basic control circuits for one stand are shown in Fig. 31, this stand having a two-armature drive. The motor fields are supplied in series from an exciter ME, which has a shunt field energised through the stand speed-setting rheostat controlled by the mill operator. The exciter also has a differential series winding which both increases the speed response of the main motor field and reduces any changes due to main motor field temperature variation.

A speed reference bus is common to all stands. This is supplied from the exciter RBE, on the left of the diagram, which is energised through a motorised potentiometer, the control of which governs the acceleration and deceleration of the whole mill.



CMA Compounding magnetic amplifier
G Generator
GE Generator exciter
GMA Generator magnetic amplifier
M Motor
ME Motor exciter
PM Pilot motor
R Loading resistance
RBE Reference busbar exciter

Fig. 31.—Diagram of controls for one stand of a 5-stand tandem mill

The voltage across the motor armature is compared with the reference bus through the control winding of a push-pull magnetic amplifier GMA, which in turn excites the field of the generator exciter GE supplying the parallel-connected fields of the generators G1 and G2.

This system provides a closed-loop control of motor terminal voltage, maintaining it at a value equal, but for the small controlling error, to the reference bus voltage. With such a system the stand voltages are matched but the regulation due to IR drop remains.

The regulation is controlled by introducing a voltage into the GMA control circuit from the compounding magnetic amplifiers CMA, by means of the loading resistance R. A control winding of CMA is connected across the compoles of one of the motors and so carries a current proportional to the armature current of the motor. The output of CMA and voltage across R are therefore proportional to the motor IR drop. By making the voltage across R equal to the motor armature IR drop and opposing the motor terminal voltage, the control winding of CMA would compare the motor e.m.f. with the reference bus. Such a system has no regulation and would not be practicable, as the smallest error in field setting on one stand would cause an excessive change in tension between that and adjacent stands.

Some regulation must be left in the system, and this can be arranged in two ways. Firstly, an extra winding on CMA is excited also from the motor compoles but in opposition to the first. This second winding has a rheostat in series which is coupled to the reference bus exciter field potentiometer and graded so that its current is also proportional to the reference bus voltage. The second winding causes a drop in speed of the mill which is proportional to actual speed as well as load, and therefore tends to maintain constant interstand tension over the whole Ward-Leonard range. Secondly, regulation can be introduced by reducing the effect of the first winding to say 80 or 90% IR compensation. Unlike the first system this gives increasing regulation as the speed of the mill falls, though the magnitude is much less than the natural IR drop effect.

For rather complex reasons an increased regulation is desirable at thread speed on high-speed tinplate mills, for which the second system is more suitable. In practice, operating conditions determine whether either or both systems of regulation are introduced.

PROCESSING LINES

All the drives considered so far have been concerned with the reduction of the cross section

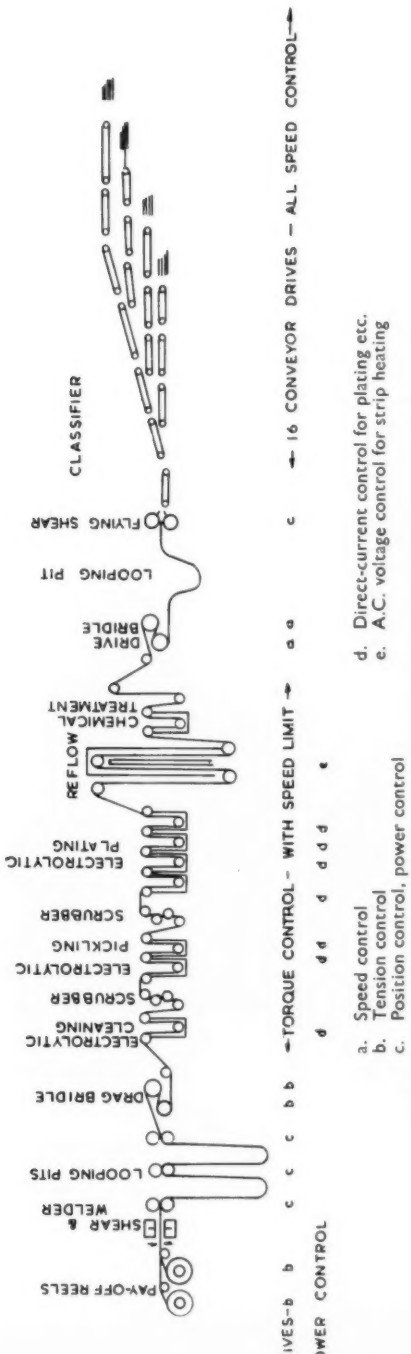


Fig. 32.—Section through electrolytic tinning line, showing the various types of control

of the metal by rolling in various ways. While a number of the various products of the steel industry can be used in the form in which they leave the mill, e.g. structural mill sections and heavy plate, a considerable proportion is processed in some way both between rolling operations and after completion of reduction to the finished gauges.

The processing may take the form of pickling to remove hot mill scale, electrolytic cleaning to remove rolling oil before annealing, annealing to give ductility, tinning or galvanising for surface protection, side trimming, slitting and shearing.

Originally these processes were carried out slowly in simple continuous lines or by individual handling of sheets. As the production capacity of the mills increased, continuous high-speed processing lines were developed to handle the greater output. At present, speeds of up to 4000 feet per minute are used on tinplate side trimming lines.

As the end products and their rates of production vary, so do the layout, speed and operational requirements of the processing line. This results in an infinite variety of designs, each tailored to suit specific conditions. While it is impossible to generalise on the control of processing lines, the types of electrical control may be classified under these broad headings :—

(*a*) Speed controls.
(*b*) Tension or torque controls.
(*c*) Position controls.
(*d*) Direct-current control for electrolytic processes.
(*e*) A.C. voltage control for strip heating.

Controls of all these types are found on electrolytic tinning lines which may therefore be taken as typical of the more advanced lines.

Fig. 32 shows a section through a tinning line with the controls for the various drives and power supplies classified as above. The line operates at about 1000 feet per minute and converts coils of steel, cold rolled to about ·01 inch thick, into sheets of tinplate having a uniform layer of bright tin either side about ·00006 inch in thickness.

Coils of strip are delivered from alternative pay-off reels to a welder, where ends of successive coils are joined, and thence through pinch rolls into loops which provide sufficient storage to allow continuity of processing while the pay-off reels are stopped for coil changeover. The strip is carried on driven rolls through electrolytic cells where it is cleaned, pickled and then tinplated.

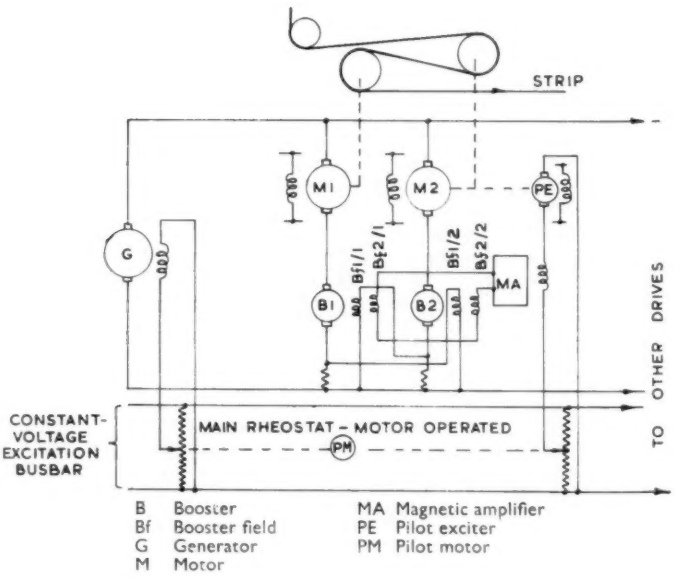


Fig. 33.—Speed control for drive bridle

Subsequently the strip is electrically heated to melt and brighten the tin, is oiled, sheared and automatically classified into piles of prime and various types of reject sheet.

In all, some 75 d.c. drives are used, each individually controlled under a closely co-ordinated Ward-Leonard system, with some 3 megawatts of low-voltage d.c. power for the electrolytic cells and some 3 MVA of 50 cycle a.c. power. Typical controls for a tinning line are described below under the appropriate headings.

Speed Controls

While many of the drives have speed control of one form or another, the drive bridle which is the master drive for the whole line has consequently the most critical. Fig. 33 shows a typical control for a drive bridle.

In order to provide the necessary tractive effort the strip is passed around two rolls which are driven by individual motors of about 50 and 100 h.p. The two motors obtain their supply from a generator G, which also supplies most of the other d.c. drives of the line and so provides a basic Ward-Leonard control of the line speed. Each motor M1 and M2 has in its armature circuit a booster B1 and B2 which provides both load sharing and fine control of speed. Load sharing is accomplished by the use of cross-connected fields Bf1/1 and Bf1/2, supplied from resistance in the motor armature circuits. Accurate control of speed is achieved by comparing the actual speed of one of the motors with the chosen reference set on a potentiometer. The speed is measured by a pilot exciter PE, coupled to one of the motors, but as the strip effectively couples the two drives, the output of the pilot exciter is proportional to the speed of both drives. Any error in speed appears as a voltage across the winding of an amplifier, shown as the magnetic amplifier MA, though any other type of power amplifier could be used. The output of the amplifier feeds a correcting signal into both booster fields Bf2/1 and Bf2/2, thereby adjusting the voltage applied to the motors to match their speeds to the set reference.

Tension Controls

Tension controls are applied to the pay-off reels and to the drag bridle. The latter is arranged similarly to the drive bridle but is located as shown in Fig. 34, at the ingoing side of the main process section, and sets up back tension to ensure correct tracking of the strip through the process section.

The two machines DG1 and DG2 therefore act as drag generators and have fixed fields ; the torque they absorb, which corresponds with the back tension in the strip, is proportional to their combined armature current.

In this case a similar arrangement of booster fields is used to that for the speed controls, but the amplifier controlling them compares the difference between the actual armature current flowing, measured as the drop across a resistance unit in the combined armature circuit, and a potentiometer manually set to a position corresponding with the required tension. Any difference between actual and required tension is applied to the amplifier,

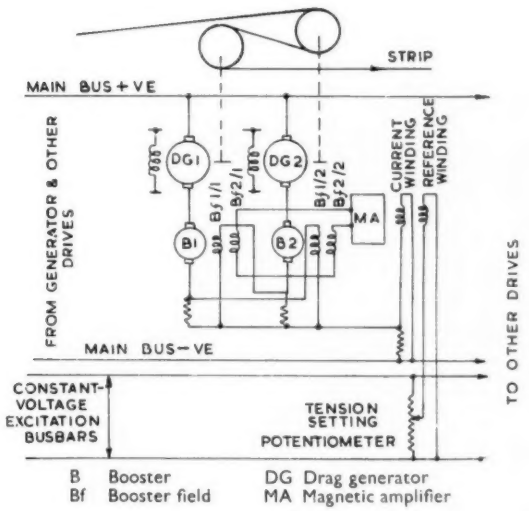


Fig. 34.—Tension control for drag bridle

which then provides the necessary correcting signal to the booster fields.

Position Controls

Position controls are used to maintain the desired depth of a free-hanging loop of strip on many processing lines. On the tinning line they are used for two purposes. Firstly, several deep loops are used to provide an accumulation of strip which may be expended when the entry end is stopped for coil changing and the process section continues operating. Secondly, a shallow loop is arranged from which the strip enters the flying shear. The purpose of this is to ensure that the strip is not under tension, so that it can be positioned by side guides without damage. For either type of loop it is desirable to maintain the position of the bottom of the catenary, which is detected photo-electrically, at a chosen level.

Fig. 35 shows the scheme of control used for the flying-shear loop. This is the 'modulated loop control' in which a bank of about 6 photocells is focused on a light source (usually fluorescent tubes) on the opposite wall of the looping pit. The cells and light source are positioned so that their centre-line corresponds with the desired loop depth. As the loop moves down the pit the light source is progressively hidden from the photocells. The output of all the cells is added and the sum is compared with a reference corresponding with half the cells hidden. Any difference between the sum output of the cells and this reference is applied to an electronic push-pull amplifier feeding trimming fields on the generator supplying the shear motor.

In this way, if the loop is high, the increased output of the photocells gives, through the amplifier, a reduction in the net field of the shear generator and a reduction in speed of the shear motor. As the speed of the strip entering the loop from the tension bridle is constant, the reduction of shear speed causes a lowering of the loop until balance is reached. Similarly when the loop is low the reduced photocell output causes an increase of shear motor speed to raise the loop.

In many cases where the loop depth is not so critical a power amplifier can be omitted and two photocells arranged instead to operate relays which insert or remove resistance from the generator or motor field circuits as the loop rises or falls. This is commonly called 'step control' as opposed to the more complex modulated control.

Direct-current Control for Electrolytic Processes

One of the most critical controls on an electrolytic tinning line does not involve motors. It is the current control of the plating supply in which direct current, usually up to about 7500 amperes

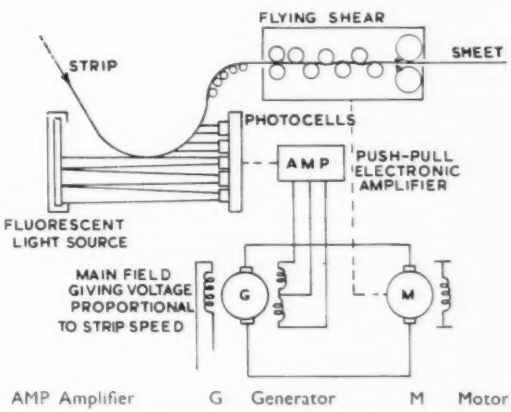
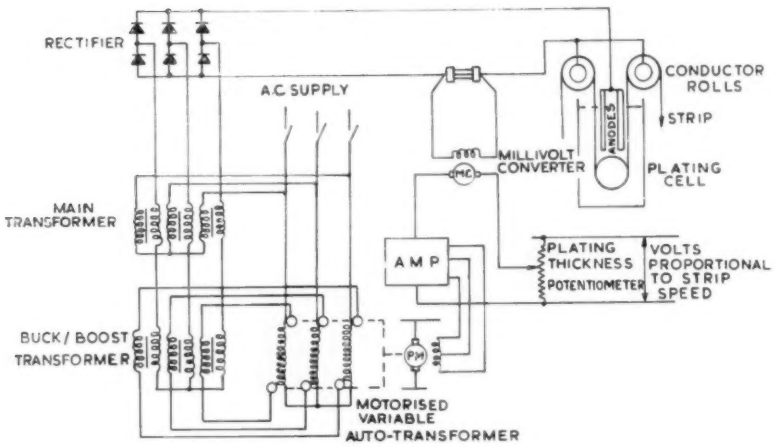


Fig. 35.—Position control for strip in flying-shear looping pit



AMP Electronic amplifier
MC Millivolt converter
PM Pilot motor

Fig. 36.—Current control for plating supply

at about 18 volts for each of 8 or 16 plating cells, is maintained proportional to strip speed and required plating thickness. As the quantity of tin deposited is dependent upon the current flowing, this current must be accurately controlled. In practice, accuracies of about $\pm 1\%$ over a 20 : 1 range are achieved.

The simplified control scheme for such an equipment is shown in Fig. 36. The d.c. supply for plating is obtained from a six-phase metal-plate rectifier. Two identical rectifier transformers are used, one with its primary connected directly to the power supply and the other with its primary supplied from a motorized stepless auto-transformer. This auto-transformer may, dependent on the position of the moving contacts, cause the associated rectifier transformer to buck or boost the other rectifier transformer, so that a full range of voltage is applied to the rectifier. The output of the rectifier unit is measured by a shunt, across which is connected the field of a small d.c. generator which boosts the shunt voltage to about 80 volts. At this level the generator output may be compared with the voltage from a potentiometer set to the required plating thickness and fed from a pilot exciter driven at line speed. Any difference in voltage represents an error in plating current and is applied to an electronic amplifier feeding the pilot motor of the auto-transformer. The pilot motor moves in a direction to raise or lower the output of the auto-transformer, and hence the rectifier voltage, to maintain the plating current within extremely close limits.

A.C. Voltage Control for Strip Heating

Electrolytic tinplate has a matt finish which must be flow melted for commercial use. This is done by heating the strip to the melting point of tin by passing heavy alternating currents through the strip in a muffle. Fig. 37 shows the basic arrangement of the control for this. A.C. power of up to 3 MVA is taken from the line at 11 kV and is transformed down to 210 volts in two parallel-connected transformers. In series with the primary of each transformer is a saturable reactor. By varying the direct current flowing in the saturating winding, the impedance of the reactors can vary over a wide range and can thereby vary the voltage applied to the transformer primaries. The transformer secondary windings are connected to conductor rolls in contact with the strip so that the current flows along the strip between these rolls.

The control requirements of the equipment are arrived at as follows :—

$$W = S.A.C.T.$$
$$= I^2R$$
$$= I^2\rho\frac{L}{A}$$
$$= \frac{V^2A}{\rho L}$$

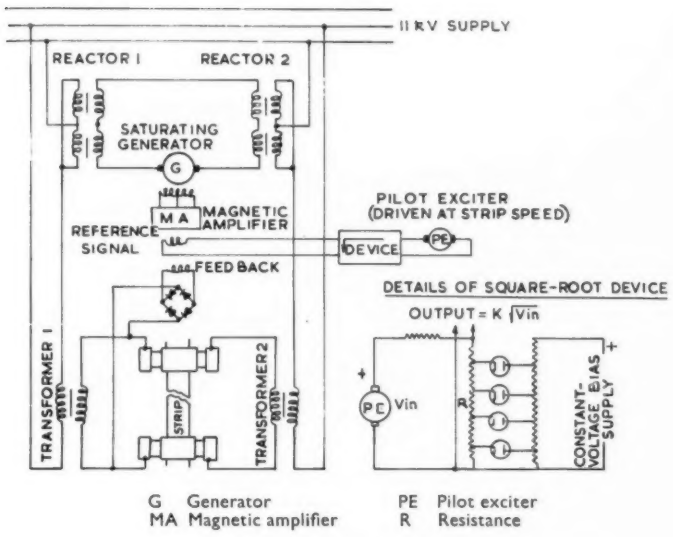


Fig. 37.—A.C. voltage control for tinplate flow-melting

where

C = constant covering specific heat and various conversion factors

W = power to heat the strip (watts)

S = strip speed (f.p.m.)

A = cross section area of strip (sq in)

T = temperature rise in strip required

I = current in strip

R = resistance of strip (variable with cross-section)

ρ = specific resistivity

L = length of strip between conductor rolls.

$$\therefore \frac{V^2 A}{\rho L} = S.A.C.T.$$

The term ' A ' cancels, giving

$$V^2 = S.(C.T.\rho.L.)$$

or $V = k\sqrt{S}$

where

$k = \sqrt{C.T.\rho.L.}$ a constant for a specific temperature rise.

It is therefore necessary to maintain the voltage across the strip proportional to the square root of the strip speed.

The square root of strip speed is obtained by taking the signal of strip speed from a pilot exciter PE, driven by the drive bridle, and applying it to a square-root device shown inset on Fig. 37. This comprises a series of diodes backing off the pilot exciter voltage against a bias potentiometer. As the pilot exciter volts rise the diodes successively become conducting and so reduce the effective impedance of the resistance unit across the pilot exciter. By suitable design the voltage across the resistance R can be made to follow a square-root law. Any difference between the feed-back voltage obtained from the main transformer secondary winding and rectified, and the reference obtained from the square-root device and tachogenerator, is applied to the control winding of the magnetic amplifier so that the saturating generator field, the saturating current and the transformer secondary output are all altered to bring the last quantity to a value corresponding with the square root of the actual strip speed at that instant.

LATEST DEVELOPMENTS IN STEELWORKS CONTROL

In this article a number of typical control schemes have been considered to show the way in which the electrical engineering industry provides for the needs of the steelworks. These schemes, while representing up-to-date practice, are being continually improved. In the past, stress has been laid mainly on the faithful obedience of the drive to the manually initiated commands, and the control scheme has been designed to achieve this with a degree of accuracy and speed of response suitable for the particular application.

In practically every case this aim has been achieved so that further improvement must be found along different lines. Two of these which form the logical continuation of the development being actively pursued are :—

(*a*) The replacement of moving elements by static devices.

(*b*) The use of automatically programmed instructions to replace manually initiated commands.

Static Devices

Any machine that rotates must wear to some extent ; this applies particularly to d.c. machines, for which regular checking of the commutator and brushgear, as well as the bearings, is needed. Furthermore, large machines need substantial foundations and in many cases provision of extensive forced ventilation and pumped lubrication systems. The advantages of the static mercury-arc converter over motor-generator sets for a.c./d.c. conversion have long been recognised but it is only now that the problems of applying converters to some types of drive have been overcome. For some years the mercury-arc converter has been used for hot continuous mills. Its application to hot reversing mills has been mentioned earlier in this article but it is very recent, as the first two mills of this type in Britain, having rectifier supply, went into operation in December 1958. The more difficult problem of applying rectifier supplies to cold tandem mills is now being tackled.

The use of high-gain fast-response servo controls in the steel industry was largely made possible by the development of multi-stage control exciters, mainly during the war years. As control schemes became more exacting so the number of exciters used increased, resulting in installations with large numbers of exciters, all needing some degree of maintenance. More recently magnetic amplifiers began to replace control exciters, in the first instance to give the advantage of better gain and response rather than the benefits of static devices. The latter advantage was recognised, and gradually magnetic amplifiers have replaced exciters for outputs up to several kilowatts. The present trend is to develop much larger magnetic amplifiers so that eventually all exciters may be replaced, as it is now often considered worth obtaining the reliability of a static amplifier even though it is more expensive than the corresponding exciter.

Yet another approach to static devices is in the switching field. Probably the greatest concern of the steelworks electrical maintenance engineer, after d.c. machines, is frequently-operating relays and contactors. Both transistors and small magnetic amplifiers can be used to replace relays and will undoubtedly do so in the future. At present their application is limited to certain isolated cases where the need to avoid conventional relay operation is most urgent. One example is for the operation of a solenoid valve on a flying shear where up to 100 operations per minute are involved. The use of a small magnetic amplifier as the switching device both gives speedy operation and avoids the frequent maintenance of the relay that would otherwise be needed. Much wider use of these static relays will occur in the future.

Programmed Control or Automation

Two of the main difficulties of applying full automation to the steel industry are the diverse range of products, and predicting accurately the conditions that might apply at each stage of the process. For instance, on a blooming mill there may be variation in size, temperature and alloy content of the ingot and in the size and shape of the required product.

Considerable skill is used by the mill drivers in operating manual controls to give an acceptable finished product at a high rate of output despite these variables. Unfortunately all operators cannot have equal skill nor can any operator demonstrate the best skill all day and every day. This factor has led to the call for automation as programmed control in the steel industry.

The first aim in applying automation to the industry has been to match, and only match, the performance of the best operator when at his peak of efficiency. To reach this stage is a considerable achievement which offers great savings in production and consistent quality, as it means that the average performance is now what was previously the best. With increasing rates of production, and with automation of the user industries creating a demand for even closer tolerance in the products of the steel industry, a demand now arises for a consistent quality better than that obtainable by the human operator. The second aim for automation in the industry is therefore to improve on the best performance of the human operator. While more difficult to attain than the first, this aim is now being achieved on certain mills.

Unlike other industries, the main aim of automation in steelworks has not been the replacement of human operators. With the present rolling techniques and design of mills there is always

a danger of rolling faults or cobbles. Where automation has been applied it has been necessary to retain the operator, if only to detect the early stages of a rolling fault such as 'fishtailing', where the end of a bloom may split and open, and to take remedial action to avoid serious damage and loss of production. Changes will be needed in the basic process of rolling to avoid completely the need for the skilled operator.

Under manually initiated control, while functions such as speed, tension, voltage or current are regulated by closed-loop electrical servo systems, the human servo-link is used to control a number of other functions. Typically the screws on a hot mill are controlled by an operator who watches a dial and controls the running of the screwdown motor to bring the screws to the position required for each pass. On a cold mill the operator watches the dial of a gauge-indicating instrument, and controls the screwdown motor by pushbuttons to give the required gauge. Before applying full automation it is necessary to replace completely such human servo links by developing high-accuracy position controls and other specialised controls such as automatic gauge control.

High-accuracy position controls suitable for rolling-mill screwdowns are a recent development, and means of obtaining higher accuracy, resolution and response rate are still being improved. Automatic gauge control for cold strip mills is a new development which is also being actively pursued.

Having provided means of controlling all the variables of the mill to suitable reference signals, fully automatic operation is possible providing the appropriate reference signals are presented in the correct combination and sequence for the piece which is to be rolled. This is done by the programming equipment.

There are considerable differences in the production scheduling and operating techniques on various mills and in various works, so that different types of automatic programming equipment have been and are being developed to meet the varying needs. These are briefly :—

(a) *Plugboard Programming*.—This is suitable where a number of similar programmes are required in succession. Usually two plugboards are provided, each to cover all variables such as screw and manipulator position and mill and tables speed for each pass through the programme. One plugboard is used while the other is set up for the next programme required.

(b) *Translator Control*.—This is suitable when a limited number of programmes are required but rapid changes of programme arise and immediate access to the correct programme is needed to avoid production delay. Telephone-type uniselectors are used, and information on the ingoing piece and the required product is set on a series of dials. The uniselector homes to a position corresponding with the programme matched to the information set on the dials. From this position other uniselectors are set to provide the correct references for the various settings of speed, screw position, etc., pass by pass for the appropriate programme.

(c) *Punched Card or Tape Programmers*.—This can also cover magnetic tape storage and is most suitable where a greater number of programmes is needed than would be possible on the translator control but where the programme needs can be anticipated sufficiently in advance to make the longer access time of no consequence. A card or section of tape is prepared for each programme, and the settings of all the variables for each pass are punched or recorded, usually in a binary code.

CONCLUSION

In this article the approach of the electrical engineer to some of the many control problems of the steel industry has been described. While the specific problems and their treatment which have been covered are but a few of the number which continually arise, the authors have set out to show by these typical cases how the electrical engineering industry has done so much to bring the steel industry to its present high level of efficiency.

The close co-operation between these industries must continue in the future to result in even greater improvements, giving benefit not only to the two industries but to the industrial life and well-being of the country as a whole.

A Method of Estimating the Fatigue Life of Aircraft Structures with particular reference to the Engine Supporting Structure

By V. H. KNIGHT, A.M.I.Mech.E., A.F.R.Ae.S., Chief Stressman, Luton Flight Establishment, D. Napier & Son Limited.

THE PROBLEM OF fatigue in aircraft structures is becoming very important, especially in civil transports where airframe longevity and utilisation are vital to the operator. Airframe flight and ground load stresses have, in the past, generally been solved by the principle of statics, and in the case of military aircraft, especially the fighter for which high rates of manoeuvres in the air are part of its main functional role, this method of solution has proved satisfactory. Because of the severe manoeuvres that the fighter aircraft may be called upon to perform, the load factors to which it is designed are necessarily high but the normal operating stresses experienced by the structure during the major part of its life are low, and therefore structure fatigue does not normally present a problem.*

The two components which experience fluctuating and reversals of stress at very high frequencies are the engines and propellers, but these are considered outside the scope of this article and it is proposed to deal with the engine supporting and aircraft structure only. The problem therefore resolves itself into assessing the endurance limit of the structure under the application of varying magnitudes of load, which becomes the fatigue life, and equating it to a load spectrum which represents the number of times loads of varying magnitudes are applied.

Fatigue Tests

To determine the fatigue limit of a structure, or as generally the case a structural component, it is necessary to resort to an actual test or, by comparison, to tests carried out on a similar component.

The component is loaded in a manner representative of the loads experienced in service, which may be under the action of bending, tension or compression or any combination of these. The applied stress may alternate from positive to negative, or from zero to positive or negative, and the component may at the same time be subjected to varying levels of steady-state stress. It can be seen therefore that the practical determination of the fatigue life of a component can be a very lengthy and expensive laboratory procedure.

It is probable that an intensive study of fatigue was first made in connection with railway rolling-stock axles, whereby each fibre was subjected to a reversal of stress during each revolution of the wheel, the early form of fatigue testing equipment being that introduced by Wöhler.

The strength of lugs in fatigue has been surveyed by Heywood[4], and in his report the available test results have been correlated to give a general picture of performance and a basis for design.

A fatigue analysis has already been carried out on the Eland Convair/Canadair CL.66 engine mounting[1], and it is upon this work that the author has based this article. Investigations into the fatigue life of aircraft wings and tail planes have been carried out by several major British airframe constructors and by the Royal Aircraft Establishment, and much research is also being carried out in the United States of America.

In fatigue investigations, pressure cabins have probably received more attention in a relatively

**It should not be interpreted from this that a structure fatigue investigation should not be carried out. On the contrary, it is not only desirable to do so but may well become a mandatory requirement.*

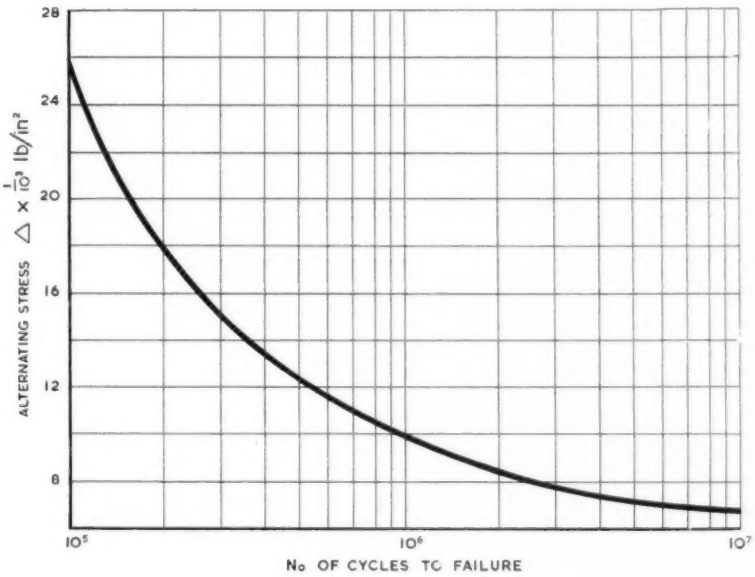


Fig. 1.—Typical component S-log N curve

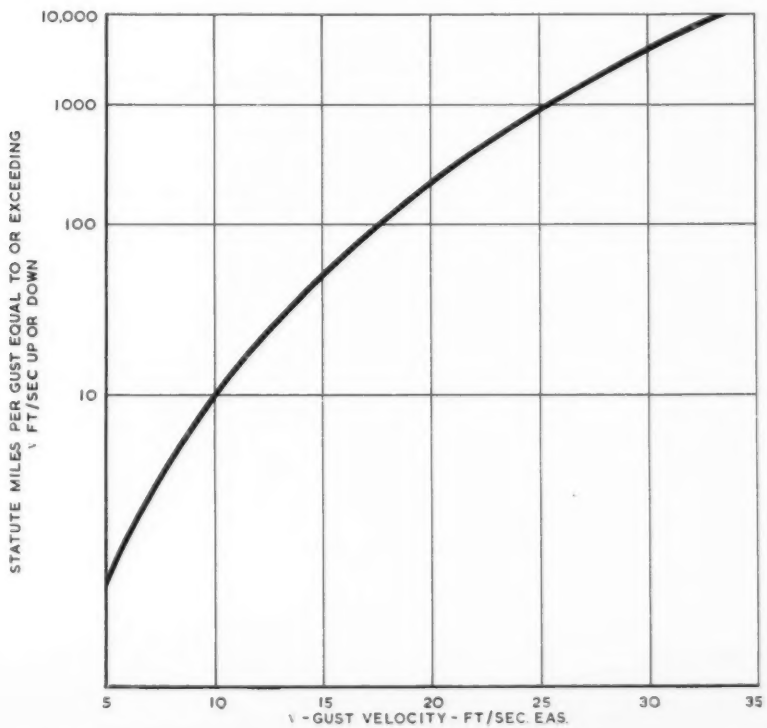


Fig. 2.—Standard gust spectrum—average gust frequencies

short space of time than any other part of the aircraft structure.

In the case of large civil transports the wing stress levels under turbulent gust conditions, although not high compared with the critical (and infrequent) gust intensity, may be sufficiently high to precipitate fatigue.

Notation

The following symbols are used in this article :

n. Number of stress applications.

N. Endurance limit at respective stress level.

Δ. Alternating stress.

μ. Steady stress.

ft. Tensile static stress.

v. Gust velocity in feet per second.

g. Acceleration due to gravity.

V. Aircraft speed (E.A.S.)

Flight Plan

In order to determine the fatigue life of the aircraft structure it is necessary to set down a flight plan which is made up of segments as follows : taxying, take-off, climb, cruise, descent, stand-off and landing. The stress levels are determined for each of these segments, and the fatigue life is based on the number of flight-plan counts that the structure can withstand before failure. Each flight plan is of a certain duration, and therefore the life can be expressed in number of hours, but this is only true if the operator does not depart radically from the flight plan. In practice this works out fairly well when a given aircraft operates a particular route.

For each component under consideration an endurance limit must be determined from laboratory testing, and the results are expressed in the form of an S-N diagram as shown in Fig. 1, giving the alternating stress plotted against the number of cycles to failure. For convenience this is usually shown in the form of varying stress intensities plotted against the logarithm of the number of cycles to failure at each stress level.

The flight plan must be determined and based on a representative number of hours duration, a typical flight plan for a medium haul transport being as shown in Table I.

TABLE I

TYPICAL FLIGHT PLAN FOR MEDIUM HAUL TRANSPORT

Operation	All-up Weight lb	V E.A.S. m.p.h.	Proportion of flight plan
Taxi out and in ..	60,000 50,000	20‡	·0425
Take-off ..	60,000	0-120	·0037
Climb ..	58,000	165	·0741
Cruise ..	55,000	270	·7280
Descent ..	55,000	250‡	·1110
Stand-off ..	50,000	150	·0370
Landing ..	50,000	110	·0037

‡ *Average*

Gust Loads

During flight, the most damaging effect to the structure is caused by the gust loads, which vary in intensity and frequency. A standard gust spectrum[2] is shown in Fig. 2, in which the gust velocity is plotted against the number of miles flown (for convenience at one altitude) per gust equal to or exceeding the value chosen ; for all other altitudes it would be necessary to apply a suitable correction factor to this curve. It is assumed that each up gust is followed by a down gust of the same magnitude, and the load produced on the structure by the change of aircraft incidence due to the gust in terms of 'g', and the frequencies for each segment as extracted from the standard gust spectra, can be tabulated as in Table II.

Assessment of Fatigue Life

The fatigue life assessment is based on the empirical working hypothesis of ' cumulative damage ' suggested by Milton A. Miner[3]. Miner's hypothesis suggests that if a component or piece of material is worked at a certain stress level which reduces its life by ' a ' per cent, then its remaining life irrespective of stress level is reduced by that amount. If it is further worked at varying stress levels to b, c, d and e per cent of its life, it will not fail providing a + b + c + d + e does not exceed 100%. Therefore, if $n_1 + n_2 + n_3$ are applications of stress at varying levels, and N_1, N_2 and N_3 are the endurance limits at those stress levels, when $\frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3}$ equals unity, failure will occur.

TABLE II

TABULATION FOR LOADING AND FREQUENCIES DUE TO GUSTS

Flight Condition	Gust Velocities v ft/sec											
	$2\frac{1}{2}$	5	$7\frac{1}{2}$	10	$12\frac{1}{2}$	15	$17\frac{1}{2}$	20	$22\frac{1}{2}$	25	$27\frac{1}{2}$	30
Cruise .. $\frac{\delta g}{n}$												
Climb .. $\frac{\delta g}{n}$												
Descent .. $\frac{\delta g}{n}$												
Stand-off .. $\frac{\delta g}{n}$												

In practice, in view of the fact that most fatigue damage is done within a fairly narrow band of gust velocities of approximately 10 ft/sec, it would appear that Miner's hypothesis is reasonable, and it is in fact generally used by aeronautical engineers. It must also be understood that in practice the figures used for gust frequencies are arbitrary, being the results of flight tests with various aircraft over varying routes and altitudes.

Stress Due to Engine Power

Having determined for a given flight plan the number and intensity of gust frequencies for the various segments, it is necessary to take into account the stress due to the application of engine power, i.e. propeller thrust and torque. For simplicity the gyroscopic couples are ignored because they are only significant under the application of intentional manoeuvres, the aircraft angular accelerations being very small for minor gust intensities.

The complete flight plan will now look something like this :—

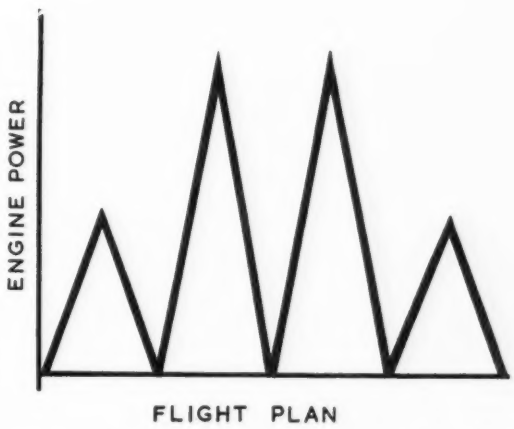


Fig. 4.—*The four power peaks in a typical flight plan*

1. Taxi out to strip, idle to half engine power.
2. Ground run up from zero to full take-off power.
3. Take-off from idle to full take-off power.

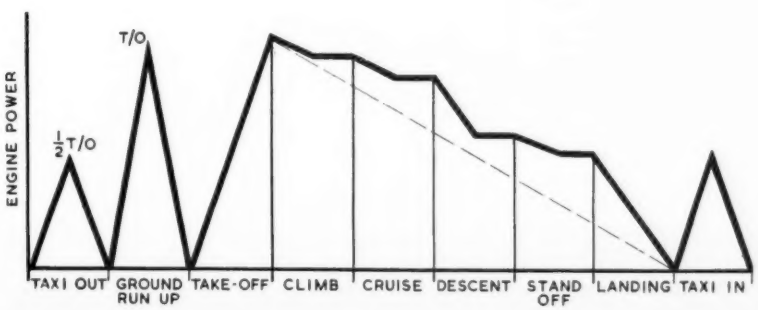


Fig. 3.
Diagrammatic flight plan

4. Climb at maximum continuous power to cruise power at altitude.
5. Descent from cruise altitude to stand-off altitude at the appropriate engine power.
6. Stand-off at appropriate altitude and engine power.
7. Landing, zero engine power and with dynamic inertias.
8. Taxi in, idle to half take-off power.

Reproduced diagrammatically the plan would appear as in Fig. 3.

TABLE III(a)

TABULATION FOR ALTERNATING STRESSES IN FLIGHT

(To be completed for each segment of the flight plan)

Height		Gust velocities up and down ft/sec (v)											
		2·5	5·0	7·5	10	12·5	15·0	17·5	20	22·5	25·0	27·5	30
Altitude feet	$\pm \Delta g$												
	Stress												

TABLE III(b)

TABULATION FOR STEADY STRESSES IN FLIGHT

(To be completed for each segment of the flight plan)

Component (1)	Stress due to 1g vertical inertia (2)	Stress due to propeller thrust (3)	Stress due to propeller torque (4)	Total stress (2) + (3) + (4)

TABLE IV

TABULATION FOR STEADY AND FLUCTUATING STRESSES ON GROUND

Case (1)	Steady condition			Fluctuating condition					
	Vertical inertia g (2)	Stress lb/in² (3)	Power s.h.p. (4)	Vertical inertia g (5)	Stress due to inertia (6)	Stress due to thrust (7)	Stress due to torque (8)	Total Stress (6) + (7) + (8) (9)	Mean stress (9) × ½
Ground run up ..	1		Take-off						
Taxi out ..	1		½ take-off	*					
Take-off ..	1		Take-off	*					
Taxi in ..	1		½ take-off	*					

* *Dynamic factors to be included.*

It can be seen therefore that as far as power fluctuation is concerned a typical flight-plan count consists of four power peaks (Fig. 4).

Combined Stresses

The flight plan can now be tabulated for each segment under two sections, one giving alternating stress together with the steady-state stress for 1*g* vertical inertia and appropriate engine power, as shown in Tables III(a) and III(b). Section two covers the stresses due to engine power fluctuations for ground run up, taxying and take-off, as shown in Table IV.

From a static analysis of the engine supporting and aircraft structure the critical joints or connections which give the lowest margins of safety are reviewed for their fatigue life.

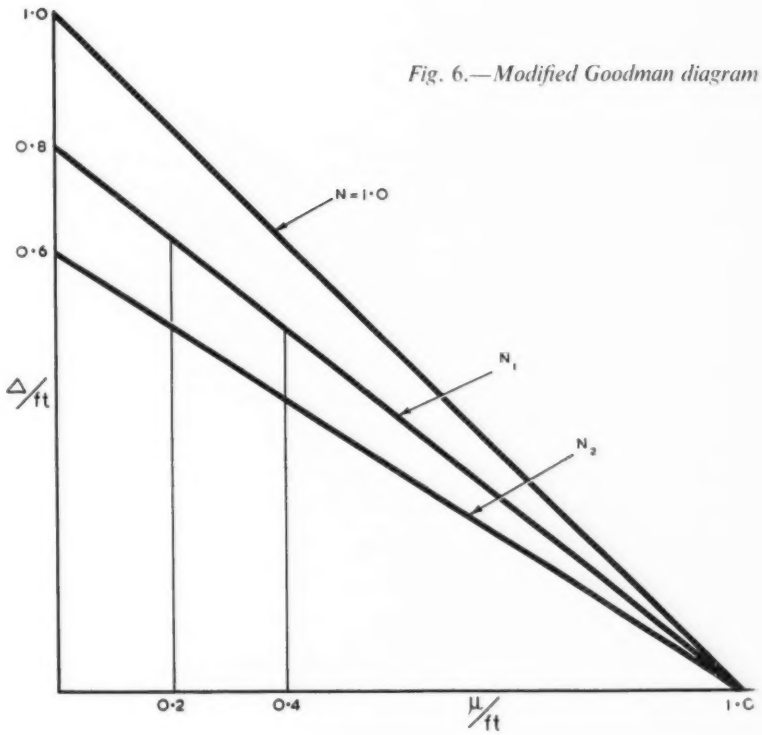


Fig. 6.—Modified Goodman diagram

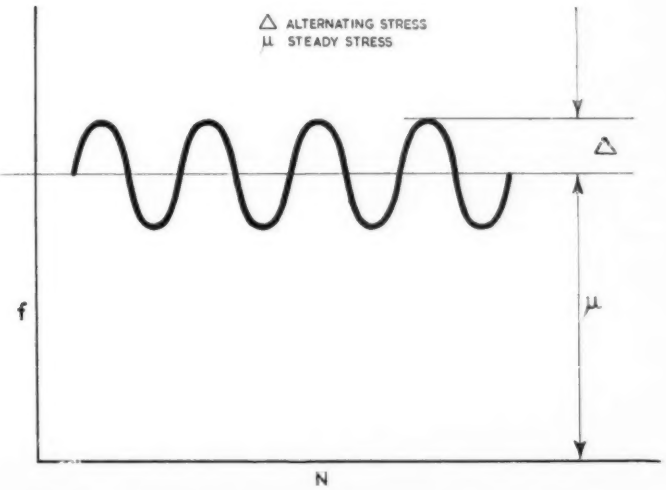


Fig. 5.—Alternating stress superimposed on steady-state stress

Representative specimens of the joints under consideration are then tested at varying alternating stresses in order to derive an endurance curve. It becomes a very lengthy and expensive procedure to conduct the tests at all steady-state stress levels experienced in each flight plan, and generally a mean or zero steady-state stress level is chosen and new curves drawn up for all other values by applying the modified Goodman method.

Firstly consider an alternating stress superimposed on a steady-state stress ; this can be represented as in Fig. 5.

It can be seen that by increasing the alternating stress the steady-state stress must be reduced, and *vice versa*, in order to keep below the static ultimate stress for the

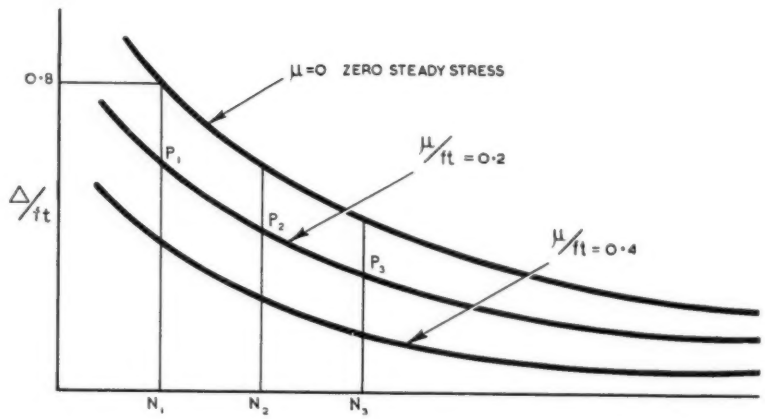


Fig 7.—S-log N curves for varying steady-state stress levels

material. When the ratio of alternating stress to ultimate static stress equals unity the steady-state stress must equal zero, and conversely when the ratio of steady-state stress to ultimate static stress equals unity the alternating stress must equal zero. This can be represented by the Goodman diagram as shown in Fig. 6.

It is now necessary to construct S-log$N$ curves for a component or material for varying steady-state stress levels, having prepared one curve from the results of laboratory testing at either zero steady-state stress level or a predetermined value, as shown in Fig. 7.

To determine lines of constant life, firstly con-consider a curve with $\mu/ft = 0{\cdot}2$ say. From the Goodman diagram in Fig. 6 read off Δ/ft and plot the point on the curve in Fig. 7. Now repeat this for varying values of Δ/ft and plot points P_2 P_3 etc.

TABLE V

TABULATION FOR SUMMARY OF FLIGHT PLAN

Segment	Climb, Cruise, Descent, Stand-off												Take-off	Taxying in and out	Landing	
	Gust velocities ft/sec															
	2½	5	7½	10	12½	15	17½	20	22½	25	27½	30				
Total 'g' counts n ..																
Fluctuating stress Δ ..																
Steady-state stress μ ..																
From S-N curve N to failure ..																
Damage n/N																Total n/N

$$\text{Damage per flight plan} = \sum {}^{1}/_{n/N}$$

$$\text{Life to failure} = \sum \frac{1}{n/N} \times \text{duration of flight plan}$$

on constant life lines N_1 N_2 and N_3 etc. S-log$N$ curves can now be drawn for various steady-state stress levels, having determined by test the S-log$N$ curve for a zero or known steady-state stress level.

A set of component S-log$N$ curves can now be prepared for all steady-state stress levels experienced by the aircraft structure on the ground and in the air.

The steady stress and alternating stress levels for each component under consideration must be determined for all segments of the flight plan and are conveniently tabulated as shown in Tables III(a), III(b) and IV.

A complete summary of the number of stress applications n, the alternating stress Δ and steady stress μ, and the number of applications to failure, can now be tabulated as shown in Table V. The total ratio n/N in each segment of the plan is summated, and the life in flight-plan counts is determined from the reciprocal of the summation of n/N. The fatigue life in hours is expressed by multiplying the number of flight-plan counts by the duration of each flight plan.

Safety Factors

It is however necessary to introduce certain safety factors to allow for the S-log$N$ curve plot scatter (i.e., variation of results from one test specimen to another) and the load application scatter. If each component tested gives very consistent results, and much research work has been done in compiling the gust spectra over a given route, then the safety factor would be low, but should not be below 1·5. One very important point to take into account, and one which is often overlooked, concerns the component surface finish. The finish of all components under test should represent that of the production article, and not be produced as a laboratory test specimen. Fits of bolts in holes must also be representative, because very misleading results can be obtained by carrying out tests on components with push or light drive fits when the production service components actually have a very free fit. Stress raisers should be eliminated at the design stage wherever possible, although in some cases these are unavoidable such as with riveted or welded joints. The fatigue life of a riveted or welded joint is much lower than that of the parent metal, because under low stress conditions plastic flow does not take place and consequently there is considerable stress variation at the joint.

Conclusion

As yet there are no short cuts which can be taken to reduce the amount of work involved in analysing the fatigue life of the engine supporting and aircraft structure, although the problem can be approached and the results presented in many different ways.

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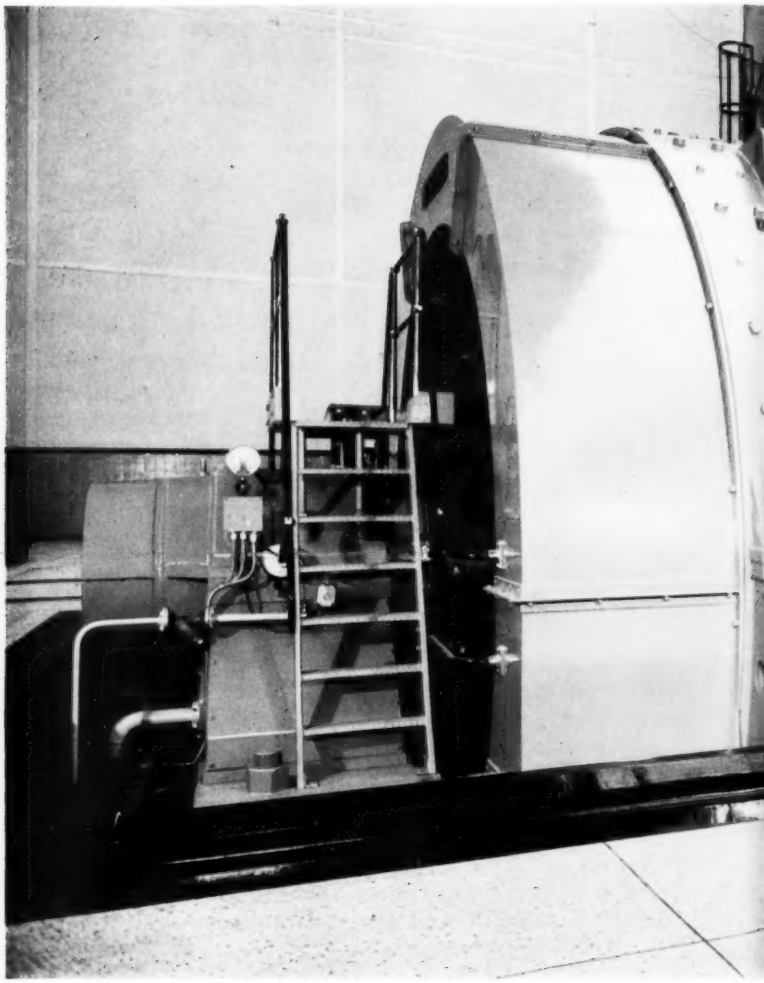
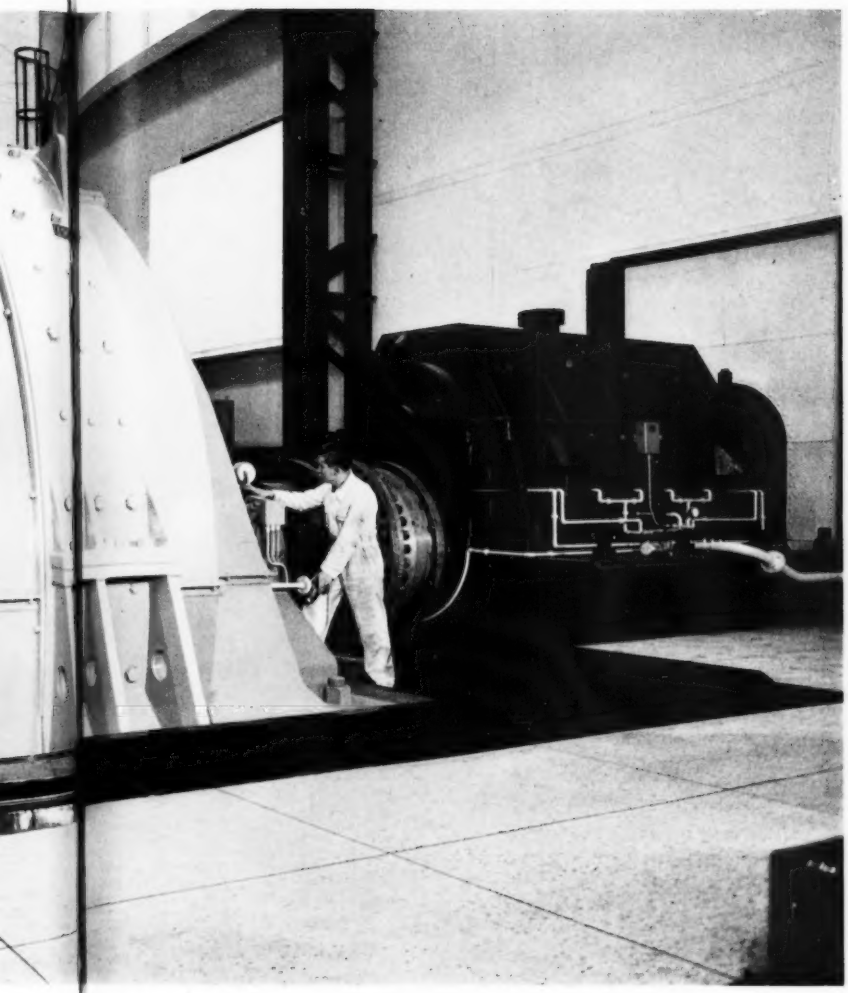


The main-drive motor of a 54 *in.* × 32 *in.* × 98 *in.* 4-*high hot reversing plate contains the main-drive motor for a new* 40 *in. blooming mill. The two motor*

Each motor has an r.m.s. rating of 5,000 *h.p. with a speed range of* 45-90 *r.p. the two sets being identical.*

The English Electric Company also supplied the drives for the bloom shear ventilation equipment.

This is typical of the comprehensive contracts undertaken by the Metal Industri

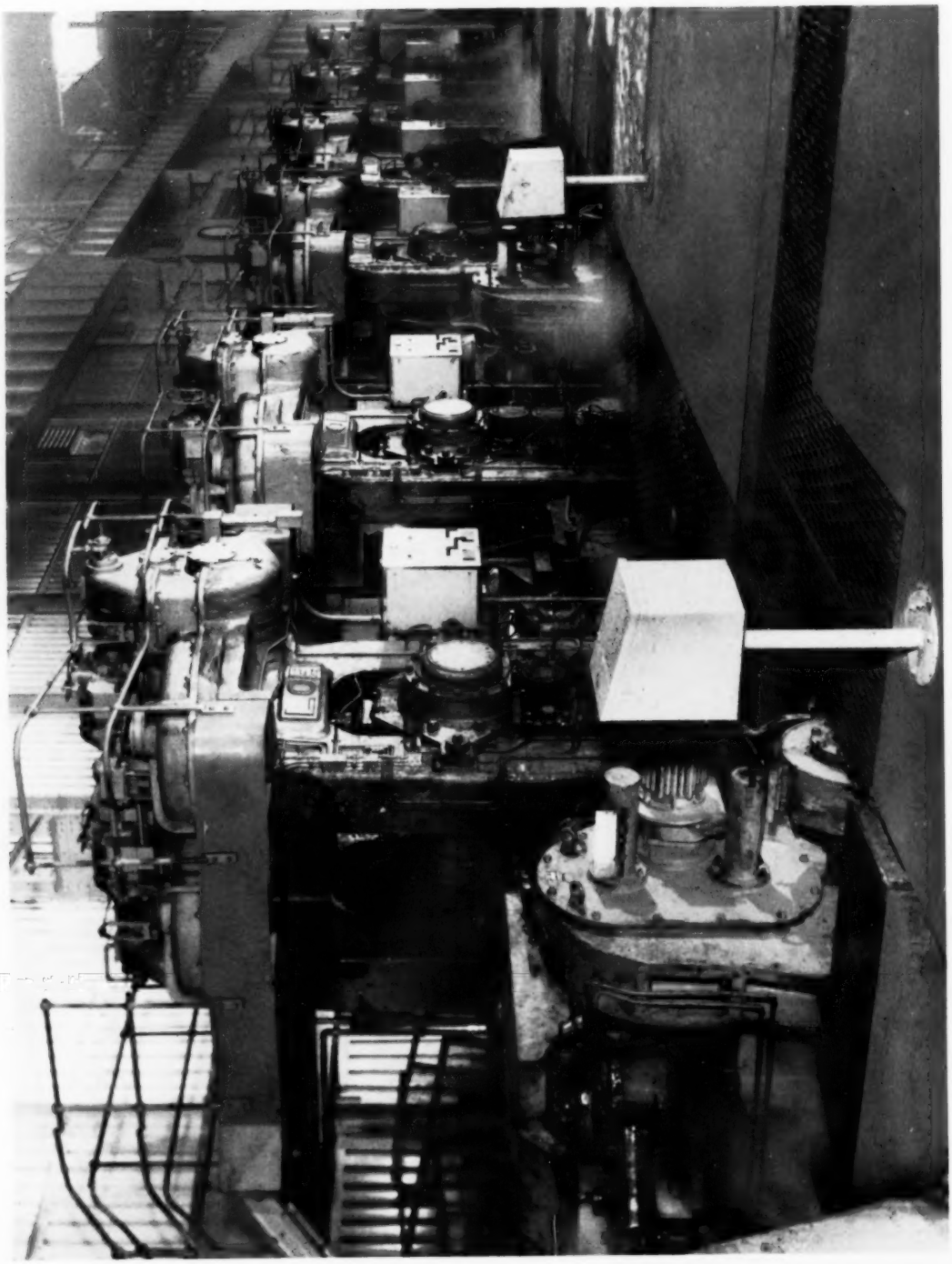


ng plate w works of The Patent Shaft Steel Works Limited. The same motor room also
o motors rating, were designed, built and installed by The English Electric Company.

-90 r.p.m at torque of 240 *metre-tons, and each is fed from a Ward-Leonard Ilgner set,*

n shear ing mill, and most of the auxiliary drives, control gear, and lubrication and

Industrie



A hot strip mill of Steel Peech & Tozer, controlled by mercury arc rectifiers

Mercury Arc Converters for Rolling Mill Duties

By K. D. PHILLIPS, B.Sc., A.M.I.E.E., Deputy Manager (Sales), Rectifier Substation Department.

MERCURY ARC CONVERTERS have long been established as a means of power supply and control for the motors of continuous hot mills; examples of these are strip, skelp, billet, bar, rod and wire mills. These converters are now also established for other types of mill including reversing mills and non-reversing mills requiring regenerative braking, e.g. cold tandem mills.

The principal reasons for the employment of mercury arc converters may be summarised as :—

1. High operating efficiency over a wide load range ; small losses at light load.
2. Reduced capital and running costs.
3. Fast response to control devices of low power ratings.
4. Absence of large rotating parts ; low noise levels and easy maintenance.
5. No addition to the short-circuit rating of the a.c. system.
6. Greater flexibility in layout of installation.

Methods of employing mercury arc converters to attain these advantages are indicated by examination of the characteristics of the converters and by discussion of existing installations.

CHARACTERISTICS OF MERCURY ARC CONVERTERS

A converter comprises a transformer, one or more mercury arc units and auxiliary apparatus. The voltage of the transformer secondary determines the maximum d.c. voltage, while the kVA rating of the transformer is proportional to the kW rating of the converter. The mercury arc unit is in series with the load current ; in every cycle, at appropriate times, positive transformer phase terminals are connected to one terminal of the d.c. system. This switching is effected by a beam of electrons, from a cathode spot on the mercury pool, travelling to successively positive anodes connected to the transformer phase terminals. In the usual circuit arrangements the current flowing from the cathode and through the d.c. system returns to the neutral terminal of the transformer secondary.

The voltage drop in the mercury arc is relatively constant throughout the normal load range and

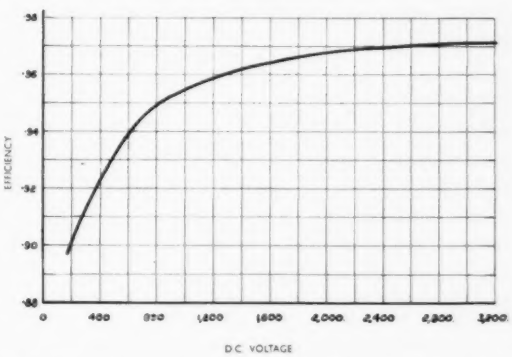


Fig. 1a.—Approximate full-load efficiency as function of d.c. voltage

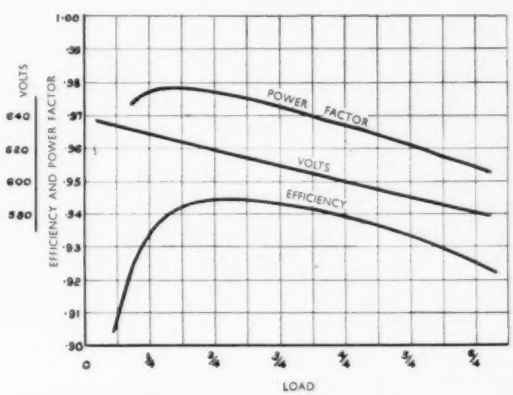


Fig. 1b.—Approximate efficiency, power factor and voltage for a typical large 600 volt 6-phase rectifier equipment

may be of the order of 17 to 25 volts. The arc loss is therefore proportional to load current and independent of circuit voltage ; in other words the efficiency of the mercury arc unit alone is roughly constant over the load range but is proportional to the circuit voltage. Fig. 1 illustrates these points but shows efficiencies also allowing for transformer and auxiliary losses. Total no-load losses are normally within the range of 1 to 3%.

Being a series device, the rating of a mercury arc unit is primarily based on current. It is of interest to note that because the voltage drop in the arc is relatively constant, rather than that of a linear resistance, the current rating of the unit is more nearly proportional to the average loading than to the r.m.s. loading. There may be slight reduction of the current rating as the circuit voltage increases, but the kW rating is increased by increasing the d.c. voltage. Subsidiary gains from increasing the d.c. voltage on a project of known kW may be a reduction in the floor area of the rectifier and also in the cost of d.c. connections.

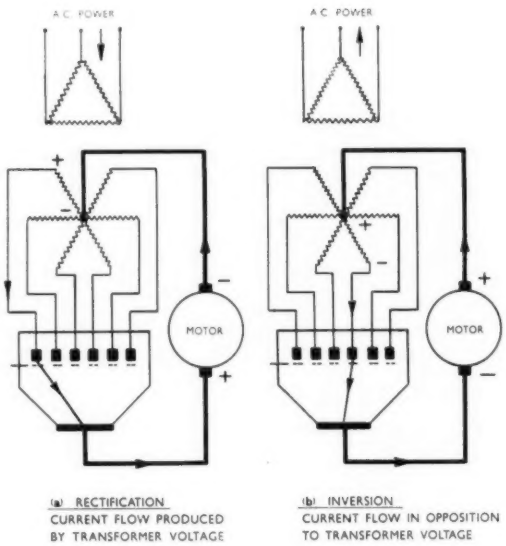


Fig. 2.—Current flow during rectification and inversion

Grid-controlled Rectification

The simplest form of mercury arc rectifier equipment has a light-load d.c. voltage determined by the secondary voltage of the transformer ; the application of full load causes a d.c. voltage drop of between 5 and 10%. If control grids are provided in the mercury arc unit, then, by delaying the firing of successive anodes, the d.c. voltage may be varied between the maximum and zero. Grid control adjustments may also be made so that the required d.c. voltage is maintained when the a.c. system voltage varies. Any delay in anode firing delays the flow of current in the corresponding transformer phase and therefore reduces the equipment power factor ; the reduction in power factor is roughly proportional to the reduction in d.c. voltage from the level obtained with no firing delay. When large amounts of d.c. voltage control are necessary for extended periods, the effect on power factor may be reduced by varying the transformer secondary voltage, for example by tappings on the primary selected by an on-load or off-circuit tapping switch.

When rectifying, i.e. when power is being transferred from the a.c. system to the d.c. system, current flows from a transformer secondary phase, during part of the positive half-cycle, through the mercury arc unit to the positive terminal of the d.c. load, through the load and back to the transformer neutral, as in Fig. 2(*a*).

Inversion

When inverting, i.e. when power is being transferred from the d.c. system to the a.c. system, current can still only flow through the mercury arc unit in the direction shown for rectification. Power transfer can only take place by making current flow through the transformer in opposition to the a.c. system voltage. The polarity of the d.c. system must therefore be reversed, i.e. with the positive side of the system connected to the transformer neutral as in Fig. 2(*b*) ; also the unit grids must be controlled to permit anode firing only during the negative half-cycles (referred to the supply). The d.c. system voltage then overrides the inherent transformer voltage so that normal commutation takes place cyclically from each anode to a more positive anode, i.e. to a transformer phase having a smaller negative voltage opposing the d.c. voltage. Adjustment of the grid circuit phasing, relative to anode voltage phasing, permits regeneration down to zero d.c. voltage. During

inversion, power is transferred to the a.c. system, but as a reactive component cannot be derived from the d.c. system the a.c. system must provide the reactive current component required for inverter operation. In effect, the inverter appears to the a.c. system as a load having a lagging power factor.

Phase Multiplication

The total number of effective transformer secondary phases determines the frequencies, and the total content, of the harmonic currents produced in the a.c. supply system, and the amplitude of the ripple in the d.c. voltage. The d.c. voltage ripple is also proportional to the grid control used. Useful data on these factors is given in British Standard 1698—Mercury Arc Rectifier Equipments. Individual equipments have transformers with either 6 or 12 secondary phases. When several converters are connected to the a.c. system the effective overall number of secondary phases may be increased to 18, 24, 30, 36 or higher. This is achieved by using extra, phase shifting, windings on the converter transformers, or by the use of separate phase-shifting auto-transformers to give phase displacements between the secondary phase groups of several converter transformers.

In the United Kingdom the public supply authorities limit harmonic distortion on their a.c. systems. This is done, as shown in Table I, by limiting the total half-hour maximum demand of rectifiers fed through a common supply point for two or more consumers. The limits are related to the overall number of effective rectifier phases and the actual short-circuit rating at the point of common supply.

TABLE I

RELATIONSHIP BETWEEN MAXIMUM RECTIFIER LOAD, NUMBER OF PHASES, AND SHORT-CIRCUIT MVA, FOR U.K. PUBLIC SUPPLY SYSTEM

Short-circuit MVA at point of common supply	Effective number of rectifier phases at point of common supply			
	6	12	18	24
	Total kW half-hour rectifier demand at point of common supply			
200	1,000	3,500	6,000	7,500
500	2,500	7,500	11,000	17,000
1,000	5,000	11,000	18,000	23,000
2,000	7,500	17,000	27,000	35,000

The supply system must also be of sufficient capacity to ensure that the repetitive peak loads of the mill do not produce voltage fluctuation sufficient to affect other apparatus adversely. A rectifier equipment cannot simulate the flywheel action of an Ilgner set in reducing the peaks imposed upon the a.c. supply system.

Overload Ratings, Temperature

Mercury arc units have small thermal mass and therefore no inherent large sustained overload capacity beyond their continuous rating. Any required overload rating may be obtained by derating the units below their maximum continuous rating. Mill duty cycles must, however, be carefully established to avoid the possible excessive capital cost resulting from unnecessarily high overload ratings. Examination of duty cycles, including test and emergency conditions, quickly establishes the r.m.s. rating and long-period overload rating. It is, however, possible that the peak rating for seconds or a few minutes will establish the size and number of mercury arc units. The ability of a mercury arc device to carry peak load depends upon various factors including the cross sectional area of the arc path, e.g. anode arm, and the vapour pressure in the path. In stable operation, positive ions, produced by collisions of electrons with mercury atoms, reduce the effect of the negative space charge (i.e. the electrons) and thus reduce the voltage necessary to maintain the arc. If there are insufficient mercury atoms in the arc path the necessary arc voltage may rise suddenly and the arc may rupture ; this is usually called ion starvation. The peak current must not be so high that ion starvation or loss of control by the grids occurs. Both these factors are moreover related to the temperature of the mercury arc unit. Close control of both maximum and minimum temperatures may be necessary for converters required to carry heavy currents instantaneously after long idle periods, particularly if large amounts of grid control are used.

CIRCUITS AND CONTROL FACILITIES

In the following list the references are mainly to a single converter, but in many cases the application may necessitate a number of equipments. These equipments may be connected in parallel or to separate sections of d.c. busbar or individually

Fig. 3.
Three 1500 kW 600 volt rectifier equipments feeding the main motors of a cross-country mill at Round Oak Steel Works

to separate motors. The two latter arrangements may be desirable on large installations to limit prospective fault currents in the d.c. system, and to give rapid speed control. Illustrations and notes on existing equipments are given later.

(*a*) *Uncontrolled mercury arc rectifier feeding motors having shunt field control and resistor starting.* This arrangement is suitable where a number of small stands or mills are connected to a common d.c. busbar. A typical equipment of this sort is shown in Fig. 3 and comprises three 1500 kW 600 volt rectifiers feeding a cross-country mill.

(*b*) *Mercury arc rectifier, normally uncontrolled, but with manually operated grid control apparatus to start one or several parallel motors having shunt field control.* This arrangement may be used instead of (a), particularly if all the motors on a common busbar are associated and it is not necessary to be able to start one motor when others are already running. If several rectifier equipments are used, this latter difficulty may be solved by having a separate starting busbar to which any motor and a rectifier equipment may be connected temporarily.

(*c*) *Mercury arc rectifier with grid control which may be used for several of the following conditions* :—

1. Starting.
2. Jogging, inching or threading ; fixed or adjustable d.c. voltage may be required ; reverse operation may be obtained by motor field reversal.
3. Setting up at reduced speed.
4. Normal operation over a range of motor speeds obtained by d.c. voltage control.
5. Automatic control of d.c. voltage to a fixed level or in response to motor speed. This control is normally given up to 150 or 200% of the rectifier current rating. Drooping or rising voltage characteristics may be required.
6. Automatic current limiting or load sharing.
7. Compensation for a.c. supply voltage variation.

Equipments falling within this category are used for non-reversing hot mills.

(*d*) *Mercury arc converter providing facilities listed under* (*c*) *but also having provision for regenerative braking and motor reversal.* Inversion for these latter facilities necessitates adjustment of control-grid phasing and also reversal of the polarity of the d.c. system. Methods of obtaining polarity reversal are described below and illustrated in Fig. 4.

1. *Reversal of motor field polarity.* The reversal time includes the time of decay

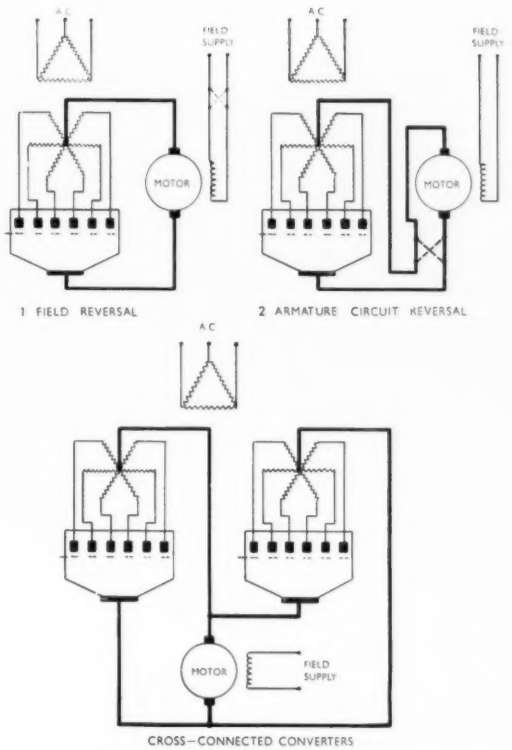


Fig. 4.—Mercury arc converter connections permitting motor regenerative braking and reversal

and reversed build-up of the motor field. The time may be considered too long in some applications ; it may however be reduced by the use of field forcing and laminated field systems.

2. *Reversal of armature connections.* A switch reverses the connections from the converter to the armature. The switch is designed for frequent operation and its duty is eased by using grid control to bring the current to zero before the switch operates. Once the switch has reversed, the motor is braked to standstill and, if required, run up to speed in the opposite direction merely by adjustment of the control-grid phasing. The dead time, i.e. during switch operation, is shorter than the time required for field reversal.

3. *Cross connected converters.* The motor is started by grid control on one converter ; braking is then obtained merely by adjustment of grid phasing on the other, cross connected, converter. If the drive is reversing, the cycle is continued by advancement of the grid phasing on the second converter so that it, in turn, acts as a rectifier and starts up the motor. The duty, inversion then rectification, is applied to each converter alternately. The arrangement eliminates time delays in the change, either way, from rectification to inversion. However, the increased number of mercury arc units and transformer windings increases both the capital cost and the losses by comparison with the field or armature-circuit reversal schemes.

Any of the these three schemes may be used for hot or cold reversing mills, but armature circuit reversal offers advantages in cost compared with cross connection, and in reversal time compared with field reversal. Cross connection may however be advisable where smooth and instantaneous transition is required from motoring to braking or *vice versa*, e.g. to maintain strip tension on an uncoiler or for individual motors of a cold tandem mill.

All of these schemes are, of course, applicable to mill auxiliaries as well as to main-drive motors. Cross connection is desirable for many auxiliary drives. Mercury arc converters are also used for the excitation of motors and generators; inversion allows for discharging the field, and field forcing can be provided by designing the converter transformer for the appropriate higher voltage necessary.

PROTECTION

Faults causing heavy currents in the mercury arc units and transformer windings may be considered separately as faults on the d.c. system and internal faults.

Faults on the d.c. system are cleared by the d.c. breakers of individual motors or by breakers in the d.c. circuits of the converters or, in some instances, by a.c. supply breakers with fast relays. The d.c. breakers must be carefully selected for adequate

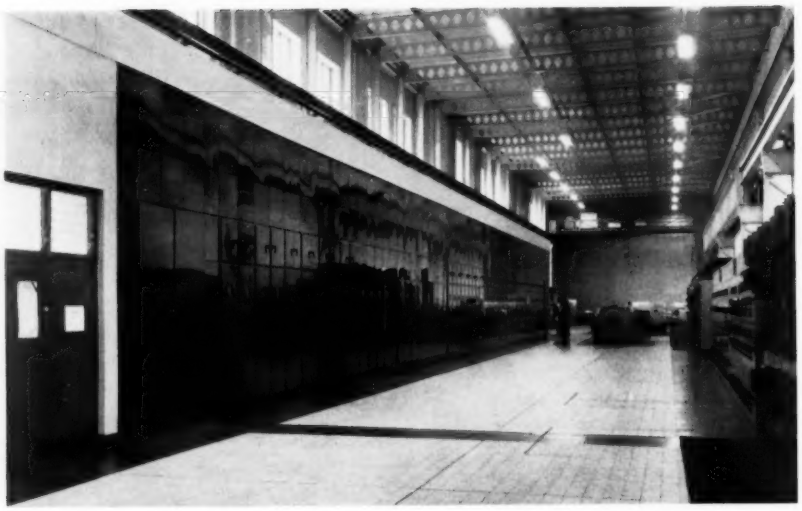


Fig. 5.
Rectifier equipments controlling the hot strip mill of Steel Peech & Tozer

speed of operation and interrupting capacity. A mercury arc converter has a prospective short-circuit current of 12 to 18 times its normal full load current rating, and allowance must also be made for fault current contribution from the motors. High-speed d.c. breakers suitable for the largest systems and highest voltages are however available.

A backfire, an internal fault in a rectifier, is due to electron emission from an anode ; it causes an anode-to-anode short-circuit, i.e. a short-circuit on the transformer secondary. The fault is also a short-circuit on the d.c. system, causing a reverse current from cathode to anode and through the backfiring phase of the transformer. Considerable experience of mill equipments has shown that back-fires are extremely rare on modern air-cooled, sealed, steel tank rectifiers. Nevertheless, fast protective devices are desirable to limit the fault current, through the backfiring anode, which may have a prospective value up to 50 to 200 times the normal anode current. On small mill equipments satisfactory protection may be afforded by fast a.c. and d.c. breakers. On large rectifier equipments backfire protection may be given by either of the following methods.

1. *Fuses in individual anode leads.* These may interrupt the faulty circuits without tripping breakers ; healthy mercury arc units continue

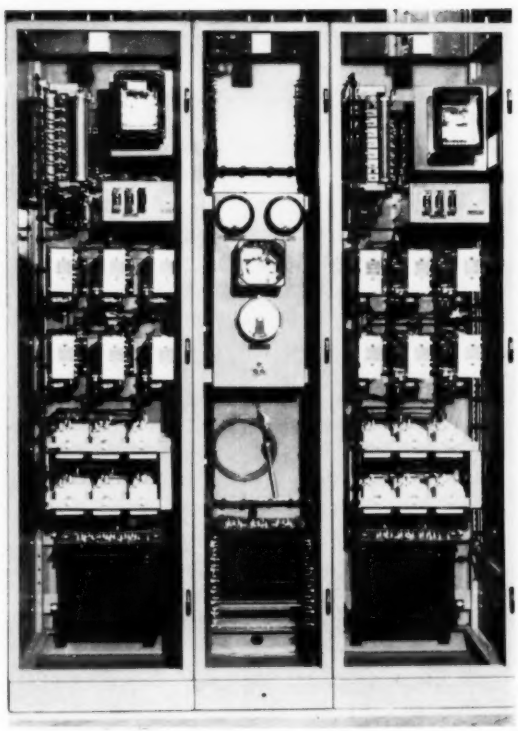


Fig. 6.—Grid control cubicle for 3500 kW 12-phase rectifier

in service. Devices are necessary to indicate fuse-blowing and possibly to take the equipment out of service. If however the remaining healthy units have reserve capacity, the devices may be arranged to give alarm only or to cause shutdown after a time delay. The possibility of continuing operation with one mercury arc unit, of a group, out of service will depend upon both the number of units and the number of transformer secondary winding groups. Converter units connected in parallel to a common 6-phase winding share the available load. Transformer secondary winding groups also share load. If a single transformer has two separate secondary windings, or has a 12-phase secondary winding, which is equivalent to two 6-phase windings, then the disconnection of one mercury arc unit will increase the load carried by each of the remaining units connected to the winding concerned without significant effect on the other winding group. In these examples, therefore, the disconnection of one unit reduces the total rating by the equivalent of two units.

2. *Arc suppression in a group of mercury arc units by application of negative bias to the control grids.* Anode-to-anode current paths are blocked as each phase reaches current zero. A reverse-current-tripping d.c. breaker is, however, necessary to interrupt the direct current passing through the cathode to the backfiring anode. This system is fast, and may if required be arranged for auto-reclosing ; however, a short time delay is advisable on reclosing, so that normal conditions are restored in the mercury arc unit concerned.

The choice between these two schemes will depend upon the difference in cost, the possible advantage of delayed shutdown, and the personal preference of the operators and designers of individual mills. A further possible, though unlikely, fault can result from loss of control by the grids, when the d.c. voltage will immediately rise to the maximum, uncontrolled, level. If the voltage prior to such a fire-through were low then the full voltage would produce a heavy overcurrent. This overcurrent would be cleared by normal circuit-breaker operation.

During inversion the voltages inside the mercury arc unit are not conducive to backfires but impose forward voltage stresses higher than those occurring during rectification. Careful design and adequate rating margins render the possibility of a resulting fire-through very unlikely. However, such a fault is severe and must be considered. If a fire-through occurs, i.e. a grid loses control, during inversion, current then flows when the transformer secondary phase voltage goes through into the positive half-cycle. The transformer and d.c. system voltages are then additive, and a heavy short-circuit current results. This continuous current cannot be broken by applying negative bias to the control grid, and it is therefore necessary to rely on quick-acting a.c. and d.c. circuit-breakers. The d.c. circuit-breaker must be capable of opening a fault circuit having a voltage of approximately twice the d.c. voltage, i.e. the d.c. voltage plus the transformer voltage. Some limitation of fault current can be obtained

Fig. 7.—A 2500 kW 540 volt rectifier equipment supplementing the capacity of the motor-generator sets feeding the hot strip mill of John Summers & Sons Ltd. The two Type OBX 3 high-speed circuit-breakers are shown in the foreground

by the introduction of extra reactance into the circuits. Anode fuses are not used with inverters because the blowing of one fuse then prevents normal commutation, and the fuses of all the anodes blow successively on fire-through fault current.

APPLICATIONS—SOME EXISTING INSTALLATIONS

The application of converters is described in the following examples chosen from a large number of equipments. In all cases robust sealed steel tank mercury arc units are used. The form of housing, the nature of the cooling system and the type of control device all vary however, and brief details of these factors are also given.

Fig. 8.—These two 3000 kW 550 volt rectifier equipments were provided for augmenting the capacity of motor-generator sets supplying the hot strip mill of Richard Thomas & Baldwins Ltd.

Hot Strip Mills

(a) The Brinsworth Mill of Steel Peech & Tozer *

Fig. 5 shows the two 3500 kW 600 volts rectifier equipments feeding the six finishing stands of the hot strip mill, together with a 1000 kW rectifier equipment feeding the last stand of the roughing train.

Each 3500 kW set includes eight steel tank mercury arc rectifiers and a 12-phase transformer, but each transformer has additional primary winding sections for a phase shift of either plus or minus 7½ degrees, so giving an overall effect of 24-phase operation. The 1000 kW set includes two rectifier units and a 12-phase transformer.

All three equipments are provided with grid control to maintain constant d.c. voltage at loads up to 150% full load, and to compensate for a.c. supply voltage variation from plus 2½% to minus 5%. Additionally, on the roughing stand rectifier the voltage characteristic may be arranged to have a pronounced droop ; this equipment also includes provision to limit the motor current to 2·5 times full load. The transformers of the 3500 kW equipments have 22-step on-load tap changers designed to cover a d.c. voltage range of 600 to 350 volts and also to compensate for periodic changes in the a.c. supply voltage. The tap changers are set for the required d.c. voltage by the pulpit operator and may also be adjusted by pushbuttons in the motor room.

The grid control apparatus, shown in Fig. 6, includes, for each rectifier phase, a saturating reactor which, upon reaching saturation, releases a steep-fronted positive voltage wave to the associated grids. The positive voltage neutralises the negative, blocking, bias normally imposed upon the grids. Control of the instant, in each cycle, at which saturation occurs, is effected by variation of a small direct current in a control winding on the reactor. Magnetic amplifiers vary the reactor control current to maintain the d.c. busbar voltage constant by comparison with an adjustable reference voltage. The circuits for the 1000 kW equipment also include

* *Descriptions of the electrical drives and automatic controls of this mill were given in the December 1958 and March 1959 issues of this Journal.*

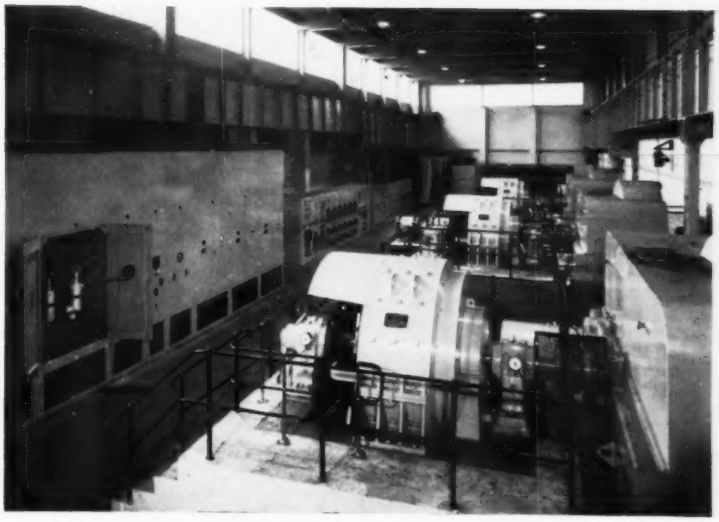


Fig. 9.—The billet mill of the Consett Iron Company has six roughing-stand drives and four finishing-stand drives controlled by rectifiers. One of the 3300 kW 660 volt rectifier equipments appears in this illustration

By courtesy of Consett Iron Co. Ltd.

a control element arranged to bias the reactor control current in response to motor load current. The 3500 kW equipments include control elements to ensure equal load sharing; the equipments can however be operated independently if the finishing-train motors are divided into two independently fed groups. The grid control circuits of both 3500 kW equipments are fed through a common, motor operated, phase shifter; this is used for starting the finishing train. The standard grid-control reactor has however sufficient range for motor starting where this scheme is more convenient.

Protection is primarily by anode fuses provided with alarm devices. The d.c. circuit-breakers are of the English Electric OB3 type with time-delayed overcurrent releases, and the a.c. breakers are fitted with both inverse definite minimum time relays and high-set instantaneous overcurrent relays.

Ventilation is basically of the straight-through type with the cold air entering a basement and flowing up through holes beneath the rectifier fan shrouds. Automatic shutters control the through flow so that a variable amount of recirculation in the rectifier room ensures a constant temperature. Automatically controlled heaters in the rectifier room ensure that peak loads may be handled immediately after any idle periods.

(b) Mills with Rectifiers and Motor-generators

Fig. 7 shows an earlier equipment rated at 2500 kW 540 volts, which operates in parallel with motor-generators feeding a wide hot strip mill. Grid control is used to maintain constant d.c. voltage and to ensure load sharing with the generators; a moving-coil regulator, with compounding coils, acts upon the grid gear. The mill motors are started by the motor-generators, and the rectifier equipment is switched in when the busbar voltage reaches the normal level. Protection is by rectifier arc suppression combined with d.c. high-speed breakers. Air is drawn upwards through the floor from a basement, but recirculation in the rectifier room permits the maintenance of the desirable minimum air temperature.

An early example of some interest, where rectifiers were provided to augment the output of generators feeding the motors of a wide strip mill, is shown in Fig. 8. Two 3000 kW 550 volt rectifier equipments operated in parallel with nine 1834 kW generators; normally however the apparatus was divided into two sections, unconnected on the d.c. side, so as to limit prospective fault currents. Rectifier protection was by arc suppression combined with two high-speed d.c. breakers per equipment. The grid control apparatus was responsive to moving-coil voltage regulators and

Fig. 10.—The 18-stand rod mill of The Lancashire Steel Corporation is controlled by two 2200 kW 660 volt rectifier equipments

these had compounding coils to ensure that the rectifier loading was matched to the generator loading; in addition, magnetic amplifiers acted on the compounding coils of the generator regulators to correct for any difference in the voltages of the two sections of d.c. busbar. The normal voltage range, in which constant voltage was maintained up to 150% load, was from 550 to 450 volts. A tap changer on each transformer covered this range and also allowed for a.c. supply voltage variation between plus 5% and minus 10%. The tap changers did not operate when there was material in the mill, but otherwise they automatically corrected for non-transient variations in supply voltage and also changed to the correct setting when the position of the mill speed controller was altered. Ventilation was straight through the floor via a basement; automatic control of air flow and of heaters ensured reasonable temperatures under load and idle conditions.

Billet Mills

The first rectifier-fed large billet mill in the United Kingdom, commissioned early in 1953, includes two 3300 kW 12-phase rectifier equipments ; one of these is illustrated in Fig. 9. The d.c. voltage may be set by on-load tap changer within the range 300-660 and is maintained constant by grid control governed by a moving-coil regulator. The transformers are rated at 4400 kW each and provision is made for the addition of corresponding extra mercury arc units. Protection of the rectifiers is by arc suppression and two high-speed d.c. breakers per equipment.

Another example includes two 2500 kW 850 volt rectifier equipments in which the grid control apparatus responds to magnetic amplifiers to give constant d.c. voltage. Magnetic amplifiers have the virtue of robustness and reliability and also give fast response ; this type of control device has become standardised for most rectifier equipments associated with mill drives.

Rod Mills

A copper rod mill commissioned early in 1952 includes a single 800 kW rectifier equipment which may be operated at either 440 or 330 volts. The grid control apparatus responds to a moving-coil regulator.

An 18-stand rod mill commissioned in 1953 includes two 2200 kW 660 volt rectifiers shown in Fig. 10. The voltage may be varied down to 300 by on-load tap changers, while the grid control apparatus is governed by electronic regulators. Tap changing is permissible with material in the mill because of the high speed of the electronic regulators ; a tap-changer operation produces no observable indication on a voltmeter. More recent mills of this type employ magnetic amplifiers in place of the electronic regulators.

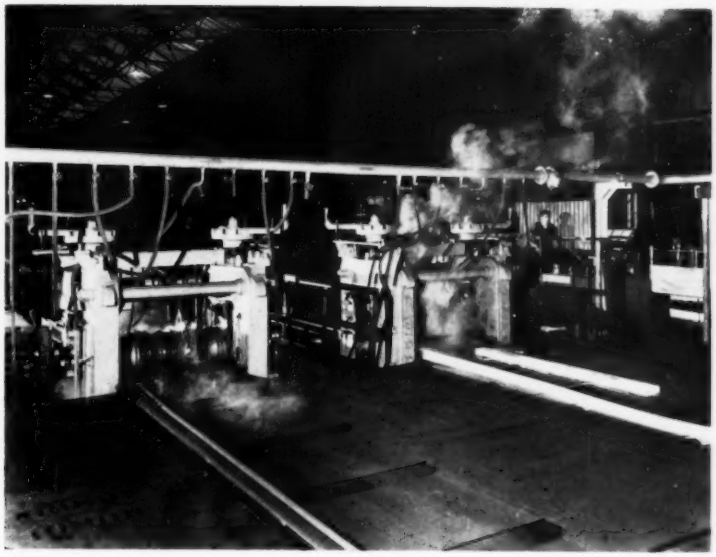


Fig. 11.
The first converter-fed reversing mills in the United Kingdom, at Darlington & Simpson Rolling Mills Ltd

The two transformers are 6-phase, but one has a star primary and the other a delta primary so that the overall effect is of 12-phase operation.

Two very similar rectifier equipments, each rated at 2000 kW, were commissioned in Norway in 1955 with a continuous 19-stand rod and bar mill. Each equipment has its own electronic regulator so that the d.c. busbar may be divided, but if parallel operation is required a supplementary control device ensures equal load sharing.

Reversing Mills

(*a*) 750 *h.p. Reversing Mills*

Two reversing mills (Figs. 11 and 12) commissioned in December 1958 and February 1959, each include a 750 h.p. motor fed by a 600 kW mercury arc converter. Each converter comprises a 6-phase transformer, two mercury arc units and an armature-circuit reversing switch. Magnetic amplifiers act directly upon the grid control apparatus and also control the motor field-weakening range. A tacho-generator indicates the speed, and its output is compared with a reference

Fig. 12.—*Two* 600 *kW converter equipments feeding two* 750 *h.p. reversing mills*

voltage varied by the operator's controller. When the difference in the two voltages is positive the converter, acting as a rectifier, raises the voltage. When the difference is negative the grid control apparatus operates to reduce the rectifier current to zero, the reversing switch (Fig. 13) changes over, and then the grid phasing is controlled to allow the flow of braking current. If the controller calls for reversal of rotation, then the motor brakes to standstill and immediately accelerates in the reverse direction without further operation of the reversing switch. During acceleration the motor is run up to base speed at full field by increasing the converter output voltage; the speed is further increased by field weakening. Braking from full speed is first obtained while strengthening the motor field, and then at full field by reducing the converter (inverting) voltage. Automatic current-limit circuits prevent overloading during acceleration and braking; a further circuit prevents excessive rates of acceleration when the mill is empty.

Fig. 12 shows the standard converter unit and housing developed primarily for motor drive applications. Automatically controlled heaters are provided within each cubicle, and the heating effect is conserved by an automatically controlled louvre shutter across the top of the cubicle. These arrangements ensure an acceptable minimum temperature, provided that the temperature of the ambient air in the rectifier room is not allowed to fall below 5°C.

(*b*) 10,360 *h.p. Twin-drive Mill for Consett Iron Company*

Two 4200 kW 1082 volt converter equipments under construction will feed separately the twin 5180 h.p. motors of a 132 inch reversing plate mill. The peak motoring torque is approximately 2·5 times the nominal rated torque, and the braking peak is 2·0 times the nominal.

Each converter equipment includes a 12-phase transformer, six mercury arc units, grid control apparatus and an armature-circuit reversing switch. Control is generally as previously described for the 750 h.p. mills, but speed matching devices for the two motors are also included. The transformer secondary voltage, and the grid control facilities, are sufficient to produce full motor speed at 2·5 times rated current. Each equipment also has an auto-transformer to permit adjustment of the maximum d.c. voltage between 100% and 75% by means of six off-circuit tappings. The transformers are connected to an 11 kV supply, with a fault capacity of 750 MVA, derived from a 132 kV system. Analysis of the supply system has shown that the harmonic currents produced by 12-phase operation are not excessive and that voltage fluctuations due to the varying mill load are within acceptable limits.

Here again standard steel tank converter units and cubicles, as described in (*a*), are used. In this case the cooling air is drawn from a basement and is recirculated via an air/water heat exchanger which also serves the bulk of the motor room. The motors have a separate cooling system.

Fig. 13.—*The main switchboard for two reversing mills* (*Figs.* 11 and 12), *showing the high-speed d.c. circuit-breakers and one of the armature-circuit reversing switches*

Each of the two converter equipments is protected by high-speed d.c. breakers and, on the a.c. side, by instantaneous overcurrent relays.

(*c*) 2350 *h.p. Mill for Samuel Fox and Company*

This stainless-steel sheet and plate hot mill will be controlled by a 1953 kW 930 volt converter; motor field reversal will be used for regenerative braking and reversed rotation. Peak motoring loads at full speed will be 2·5 times nominal torque, and braking peaks will be 1·5 times nominal torque.

The equipment includes a 12-phase transformer and 4 steel tank converter units as described in (*a*) The a.c. supply is 11 kV, with a short-circuit capacity of 250 MVA, but the system is derived from a 66 kV network. Protective devices include a high-speed d.c. breaker and instantaneous a.c. relay.

Cold Mills

The 4-stand tandem cold strip mill of Steel Peech and Tozer, Brinsworth, will be controlled by mercury arc converters. Each of the four 1,000 h.p. 600 volt main motors is to be separately fed by an 800 kW converter equipment. Each equipment comprises a transformer with two 6-phase secondary windings and three steel tank converter units. Two units are used for rectification while the other unit is cross connected for inversion. This arrangement permits smooth and immediate transition from motoring to braking, or *vice versa*. Magnetic amplifiers control the grid apparatus to give the desired motor speed and to control tension between stands. Protection on the d.c. side of each equipment is given by a high-speed breaker in the motor loop, together with a relay to detect excess current in the rectifier/inverter cross-connected loop and to trip the a.c. breaker; on the a.c. side instantaneous overcurrent relays are provided.

A similar equipment, rated at 240 kW 350 volts, is used for the coiler motor; in this case one converter unit is connected to each of the transformer secondary windings. The uncoiler supply, 25 kW 350 volts, and screwdown supplies, 2 x 13·8 kW 460 volts, are also obtained from cross-connected mercury arc converters. These supplies are however too small to be obtained economically from steel tank units, and therefore single anode, glass tube, mercury arc units (excitrons) are employed, generally as shown in Fig. 14. A similar excitron equipment, of 25 kW 230 volts, is used, as a rectifier only, for constant-voltage supplies. Protection of each excitron equipment is by a contactor in the motor loop, together with a relay to detect any excess current flow between either converter and its cross connected unit. This relay is arranged to trip the a.c. supply contactor. Additional protection is given by fuses in the 415 volt a.c. supply used for these small equipments. This application of small equipments is an interesting example of the trend towards the replacement of small rotating auxiliary sets by static equipment.

Fig. 14.—*Typical small excitron-type rectifier*

The four main transformers are connected to give the overall effect of 24-phase operation. The phase shifting arrangements chosen give $7\frac{1}{2}$° displacement from the rectifier equipments for the hot strip mill (described in (*a*) on page 34) and thus a measure of 48-phase operation overall is obtained. The main equipments are fed at 11 kV but this supply is derived from a large 33 kV system.

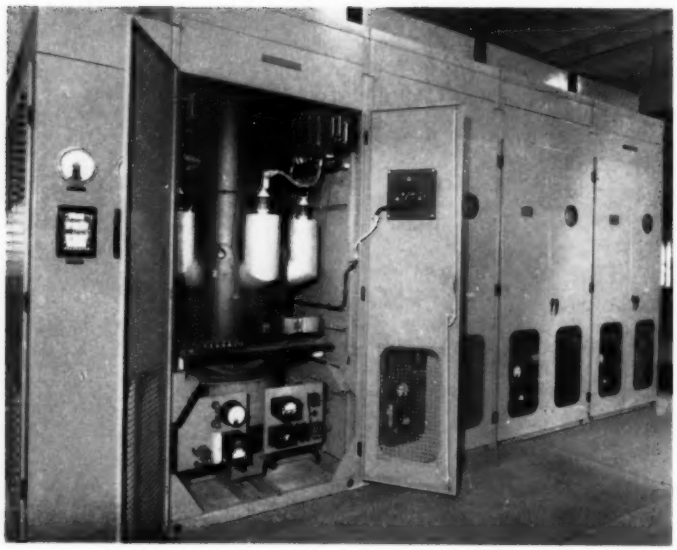


Fig. 15.—Standard steel tank converter cubicles forming a 2000 kW rectifier for a rod mill of Guest Keen & Nettlefolds Ltd., Scunthorpe.

The standard steel tank converter cubicles (Fig.15), and also the excitron cubicles, are equipped with the usual heaters and top shutters. A straight-through air supply is used but this is filtered and has controlled delivery into the bottom of the rectifier room, to avoid excessive cooling.

The skin pass mill associated with the tandem mill is also controlled by a mercury arc converter. The main equipment, which is similar to that described before, is rated at 320 kW 550 volts and includes two steel tank units for rectification and one, cross connected, unit for inversion. A small excitron rectifier equipment is used for constant-voltage supplies.

CONCLUSIONS

The few examples described show that mercury arc converters are firmly established for all types of mill drive. The advantages of these converters are obtainable wherever the a.c. supply system is satisfactory and when the motors and the control system are designed to match the converter characteristics.

Tinplate Flow-melt Equipment at the Velindre Works of The Steel Company of Wales

By J. T. BENTLEY, M.Sc.(Tech.), A.M.I.E.E., and R. QUINNEN, Grad. I.E.E., Metal Industries Division.

UNDER THE new development plan of The Steel Company of Wales, three electrolytic tinning lines for steel strip have been installed at the Velindre Works. Amongst the electrical equipment supplied by The English Electric Company is that for the flow-melt sections of the three lines.

In the modern method of producing tinplate by means of the continuous electrolytic process, the steel is passed as a continuous strip through electrolytic plating tanks, where it receives a layer of tin on each side. After this process the strip surface is matt and it is necessary to melt the tin for a short period to obtain the bright surface required on the final product.

Of the several available methods of heating the strip for this purpose it was decided that for the intended line speed and operating conditions the system of direct heating by passing alternating current through the strip would be the most economical. Heat is generated in the strip due to its inherent resistance, and the power dissipated is closely controlled so as to maintain the temperature of the strip within close limits.

General Arrangement

The following is a brief outline of the equipment associated with each of the three installations at Velindre.

The arrangement of the flow-melt tower is shown diagrammatically in Fig. 1. The current is fed into the strip by means of two conductor rolls A and B, fitted with sliprings and brushes. Fig. 2 shows these conductor rolls, the second of which is immersed in a water tank which cools the strip and solidifies the tin after flow-melting. Between these two rolls the strip is enclosed in a muffle designed to prevent heat loss from the strip.

The lengths of strip on the entry and exit sides of the heating zone pass through laminated rectangular stacks of steel, which increase the impedance of these paths and so reduce the leakage current along the strip to acceptable proportions. Rolls X and Y beyond these stacks are earthed to prevent potentials arising further along the line, the earthing being effected by sliprings and brushes to enable the leakage currents to be monitored.

The flow-melt tower is approximately 30 ft high, giving a strip heating zone of approximately 60 ft, and is designed for a maximum line speed of 1,250 ft/min.

Operation and Control

A basic schematic diagram of the electrical equipment is shown in Fig. 3.

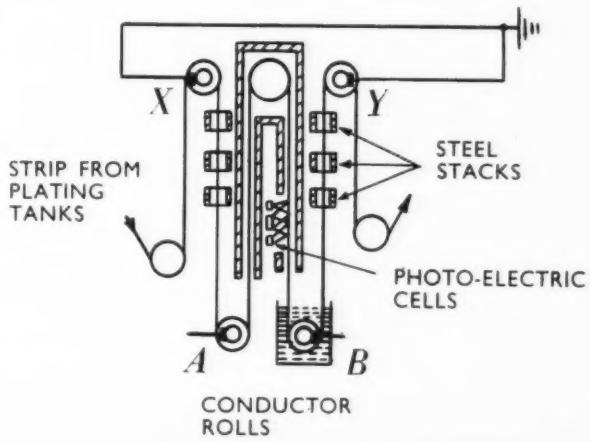


Fig. 1.—Diagrammatic arrangement of flow-melt tower

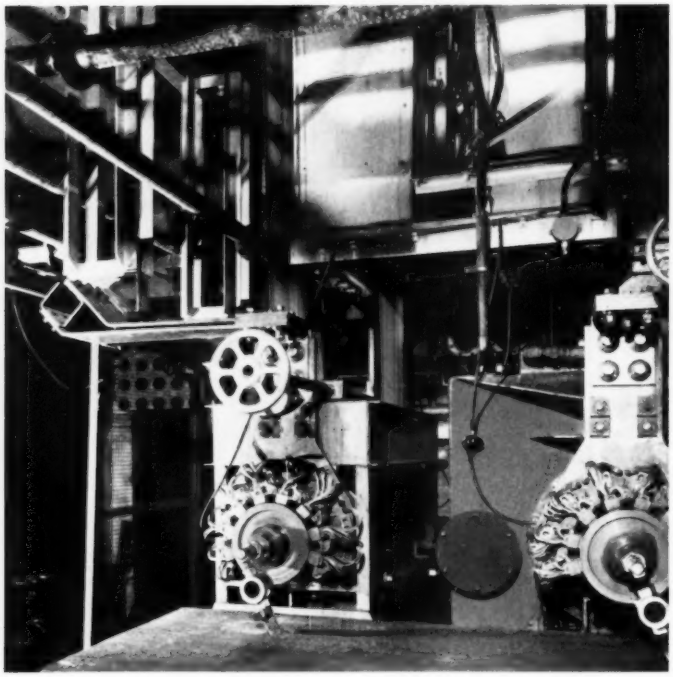


Fig. 2.—The two conductor rolls, one in water tank on right

Two 1,500 kVA transformers supply current at a maximum of 210 volts to the conductor rolls, and have their primaries connected, in series with saturable reactors, to an 11 kV supply through a circuit-breaker. The saturable reactors, which comprise two cores in one tank, have their a.c. windings on the two cores connected in parallel and their d.c. windings connected in series opposition. They are of the outdoor type and are shown in Fig. 4.

The control scheme used is capable of supplying the required power to the strip under varying conditions of speed and cross-sectional area. The following analysis indicates the basic control requirements.

The thermal power required by the strip in order to raise its temperature to just above the melting point of the tin is proportional to the weight of the strip processed per second. This weight is proportional to the product of the speed and cross-sectional area of the strip, that is :—

$$\text{Power} \propto S \times A \quad \ldots\ldots\ldots \quad (1)$$

where S = strip speed

A = cross-sectional area of strip.

Since the strip is being used as a resistance, all the electrical power is absorbed and converted into heat energy.

Therefore power supplied = $V \times I$ ..... (2)

where V = voltage between conductor rolls

I = strip current.

Combining equations (1) and (2)

$$V \times I \propto S \times A \quad \ldots\ldots\ldots \quad (3)$$

As the length of strip between the conductor rolls is constant, the resistance between rolls is inversely proportional to the cross-sectional area.

$$R \propto 1/A \quad \ldots\ldots\ldots\ldots \quad (4)$$

and since $I = V/R$

$$I \propto V \times A \quad \ldots\ldots\ldots\ldots \quad (5)$$

and equation (3) becomes

$$V^2 \propto S \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

It can therefore be seen that the correct power for any line speed is obtained by controlling the voltage across the conductor rolls in proportion to the square-root of line speed. The fact that strip cross-sectional area does not appear in the final equation indicates that the voltage necessary to give the required power is independent of the cross-sectional area.

Referring to Fig. 3, by variation of the saturating direct current supplied to the reactors, the voltage applied to the strip is controlled to the required value. A pilot exciter is driven from the line and gives an output voltage proportional to strip speed, which is then converted to one proportional to the square-root of strip speed by a device which comprises a suitable diode/resistance network. The reference voltage is then amplified to the power level required for the main-control magnetic amplifier MA2 by using the reference magnetic amplifier MA1.

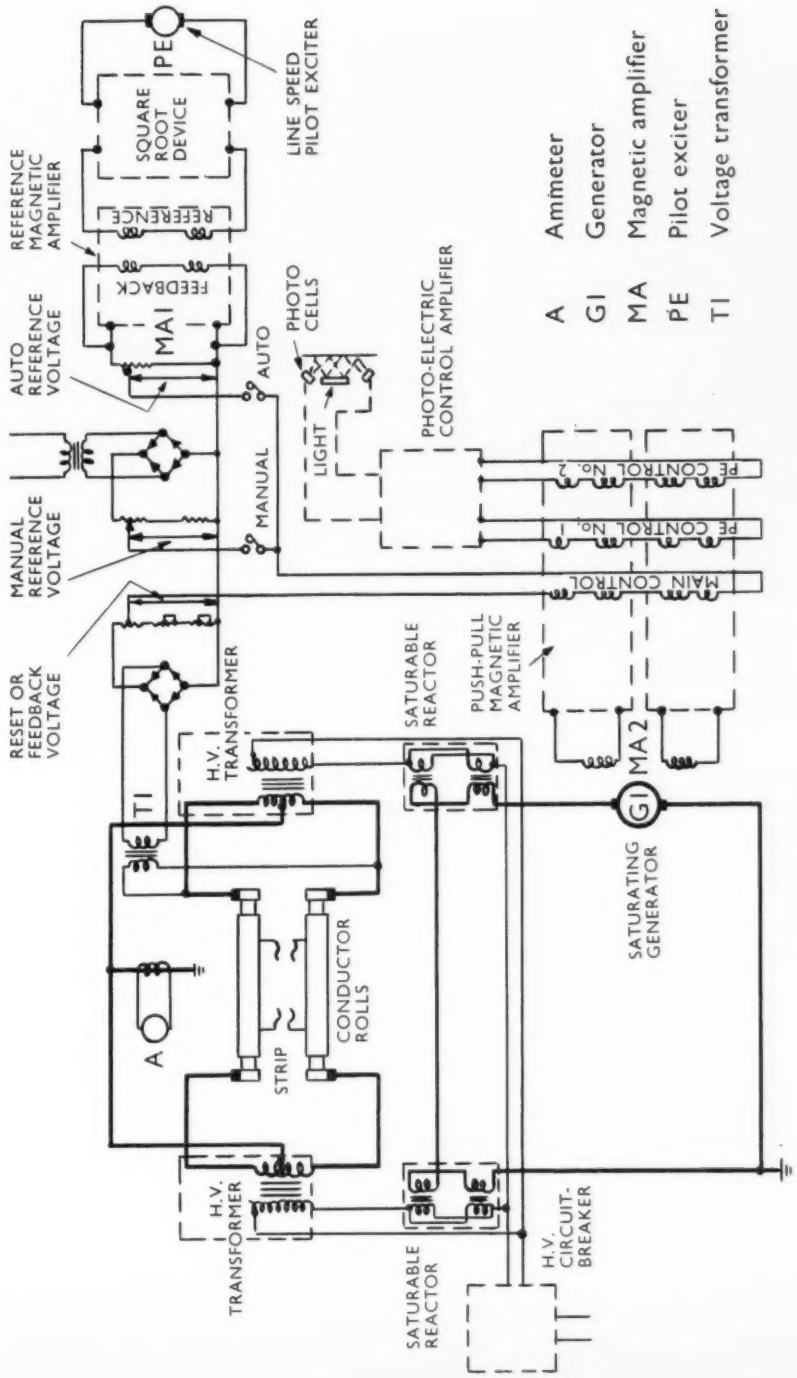


Fig. 3.—Basic schematic diagram of electrical equipment

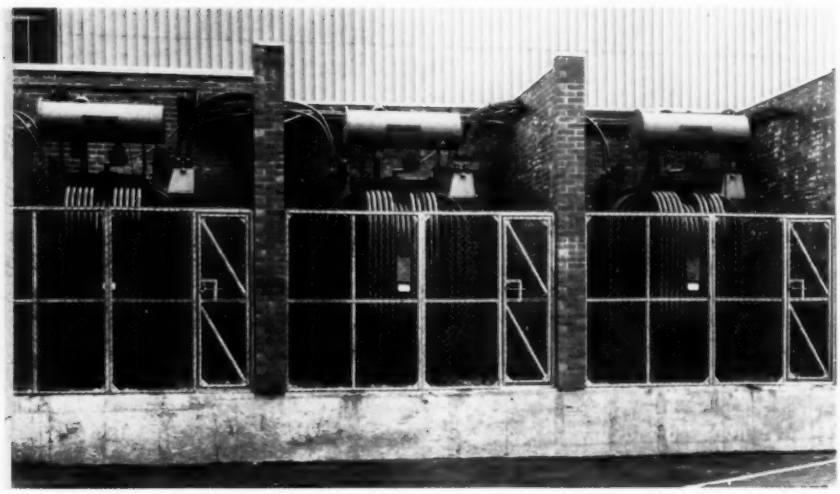


Fig. 4.
The saturable reactors for controlling the voltage applied to the strip

A feedback signal of actual voltage across the strip is provided from a voltage transformer T1, which after rectification is backed off against the reference voltage. Any error voltage is then fed to the main control winding of MA2. This magnetic amplifier feeds the fields of generator G1 supplying the saturating current to the reactors. Magnetic amplifier MA2 is arranged as a push/pull amplifier in order to obtain a rapid response for both rising and falling line-speed changes.

Due to the variations in the ingoing temperature of the strip, random heat loss in the muffle and stray draughts, the position of the point at which the tin melts (usually called the flow line) is liable to fluctuate over a considerable distance. As there is a continual temperature gradient along the length of the strip in the heating zone, any fluctuation in this flow-line position indicates a proportional fluctuation in the temperature of the strip at the point of entry to the quench tank. This temperature and the time during which the tin is molten have an important effect on the formation of the alloy bond between the steel and tin coating, and

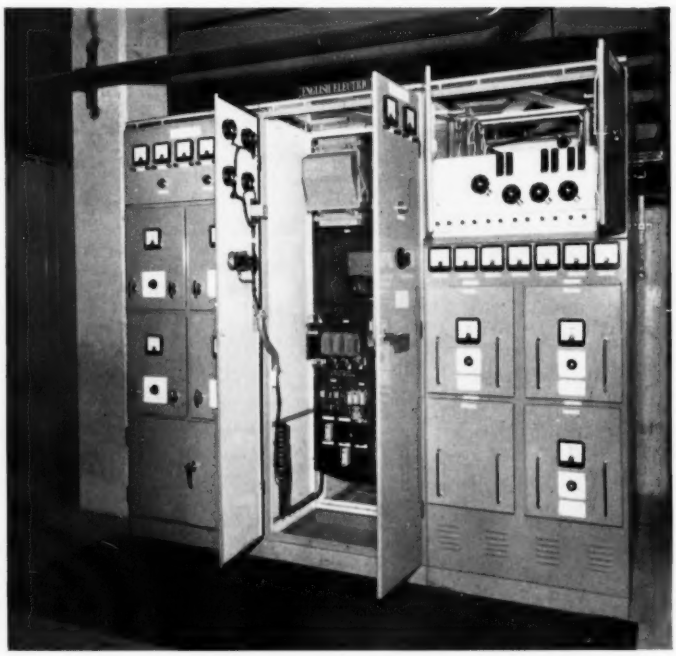


Fig. 5.—The control cubicles, containing magnetic amplifiers, electronic equipment and contactors

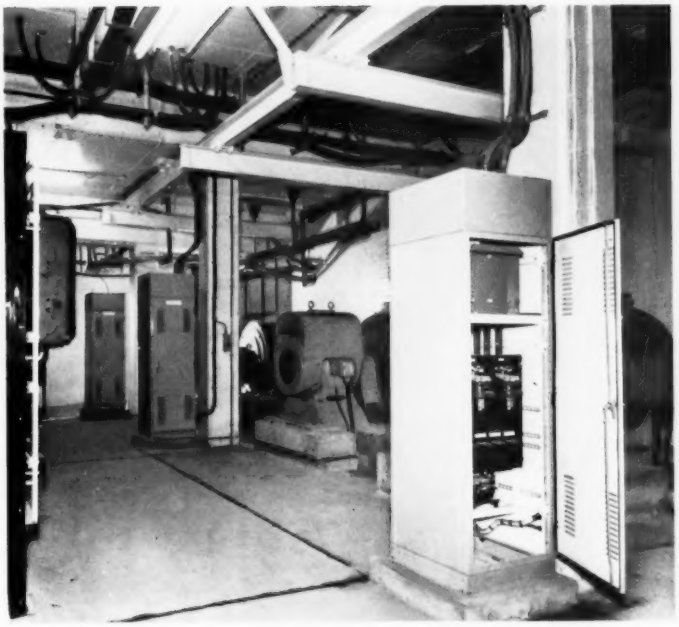


Fig. 6.—The three motor-generator sets for the three tinning lines

therefore should be closely controlled. From the foregoing it can be seen that an effective way of controlling the final strip temperature is by controlling the position of the flow line. This is done by means of a photo-electric scanning unit, acting to trim the control on MA2.

The photo-electric control used consists of a lamp which illuminates the strip in the region of the flow line, and two photo-electric cells which receive light reflected from the strip. Output from each cell is proportional to the reflectivity of the strip surface at the point viewed, and it is arranged that with correct flow-line position one cell receives light from the matt surface before flow-melting and the other from the bright surface after flow-melting. The cell outputs are adjusted to balance under these conditions and so give no output from the photo-electric control amplifier.

If the flow line moves from the optimum zone, one of the cells will start to change its output as the reflectivity of the strip viewed changes, and so cause the amplifier to give a correcting signal to one of the trimmer fields on magnetic amplifier MA2.

It has been found in practice that this system of control gives the required operation over a wide speed range. Stopping and starting conditions are rapidly compensated for by the control and produce no appreciable loss of quality in the strip.

Component Details

All the magnetic amplifiers, electronic equipment and contactor control gear are housed in the basement. They are contained in three cubicles mounted in line as shown in Fig. 5. Each cubicle is 7 ft 7 in. high, 3 ft wide and 4 ft deep. A fourth cubicle, shown on the extreme left, contains spare panels for the electronic equipment, and testing facilities.

The motor-generator set is also housed in the basement and comprises a 32 kW main generator of the protected type, driven by a 50 h.p. squirrel-cage motor of the closed-air-circuit type. Fig. 6 shows the three motor-generator sets for the three tinning lines mounted side by side. The motors are fed from the 415 volts, 3 phase, 50 cycle shop supply and are

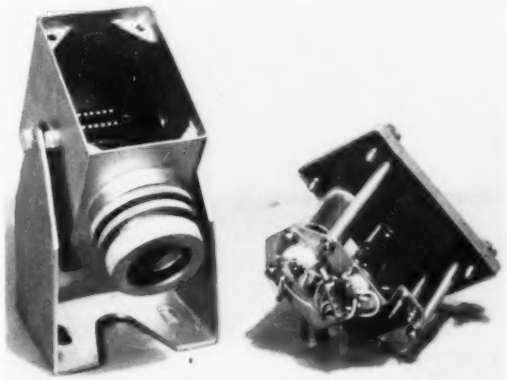


Fig. 7.—Components of photo-electric cell unit for monitoring flow-line position

started from the appropriate line control cubicles previously mentioned.

The photo-electric equipment associated with the monitoring of the flow line is mounted in the flow-melt tower between the two walls of the muffle, and the tinplate is viewed through a cut-out in the muffle wall which is covered by a window of $\frac{1}{4}$ in. armour-plate glass. The 30 watt strip lamp is fitted in a box which also contains a spare lamp for quick replacement. Mounted above and below this box are two photo-electric cell heads, each consisting of a small robust box housing a photo-electric cell, a double triode valve, used as a cathode follower, and a lens assembly, a typical unit being shown in Fig. 7. The complete assembly is arranged for easy withdrawal for cleaning and maintenance purposes.

Acknowledgments

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